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Wetland Agroecoystems in the Maya Lowlands of Belize: LiDAR and Multi-Proxy Environmental Change

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by

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Dedication

I dedicate this manuscript to you, the future student who happens to download this text in search of a citation or a method. You are intrepid and clever and worthy of your own pursuit of knowledge. I hope that when you read this, the rich livelihoods and forests in the American Tropics are protected, and the subtle expression of ancient irrigation systems still flow with lazy water during the wet season, and that the water lilies and mats of periphyton still grow there.

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Abstract

Wetland Agroecoystems in the Maya Lowlands of Belize: LiDAR and Multi-Proxy Environmental Change

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Globally, scholars have identified wetlands as critical environments for global carbon storage, water filtration, biodiversity, and many other ecosystem functions. Despite their importance, too few studies have focused on wetlands in the tropical Americas. This dissertation provides new and innovative knowledge on the extent and character of prehistoric indigenous wetland agricultural systems in the Maya Lowlands of Belize by exploring wetland development and paleoenvironmental change over the course of the late Holocene. The overall results of this project are as follows: provide new information and understanding of never before researched wetland agroecosystems; 2. determine the extent of human and environmental interaction and regional climate history in this crucial zone of the Neotropics, 3: answer questions concerning the scale and types of Maya to modern wetland management over time; 4: offer greater awareness concerning contemporary landscape degradation within critical wetland systems in the

face of future climate change scenarios, and 5. provide future resources for policy and management of American wetlands as a critical geographic area

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Chapter 1: The Importance of Wetlands for Human Ecology

1.1. Scope and Scale of Research

Wetlands cover about 6% of the Earth's surface (Figure 1.1), and they have value both for their biodiversity and their cultural heritage as a critical zone for human subsistence and settlement (Junk et al., 2013). Wetlands are a valuable but threatened resource across the globe. It is well established throughout current literature that the loss of wetlands, both through anthropogenic and natural climate change, poses a severe threat to our understanding of past human-environment relationships and to current natural and cultural resources. The benefit of wetlands to humans throughout the world is immense and includes services like carbon sequestration, biodiversity, water filtration, storm surge protection, subsistence and resource extraction, peat production, and cultural heritage. Further, wetlands provide excellent preservation for paleoecological and geoarchaeological investigations, and the waterlogged sediments within these systems yield well-preserved paleoenvironmental records that can be linked to larger cultural histories and regional climate trends.

This dissertation research focuses on a wetland system located in the northern Neotropics, along the modern Guatemala, Belize, and México borders. Neotropical wetland system exist at a smaller scale than other well studied wetlands, such as the sprawling peatlands of Canada or the productive paddy rice wetlands throughout Asia, though the true size of Netropical wetlands are poorly constrained due to lack of study. Neotropical wetlands are poorly studied in regard to function, form, and environmental history. Research has only begun to test the geochemical, biological, and geographical components of wetland systems in this region, as well as the relationship that these systems have with societies throughout history. Studies conducted in well researched wetlands across the globe demonstrate the value of such systems in regards to ecosystem services, water quality and filtration, cultural heritage and food production. Further, these systems are linked on a global scale to climate relevant gases, and serve as both sinks and sources for such key gases such as methane and carbon dioxide. Neotropical wetlands should be considered in regards to policy, economics, and the carbon trading market. It is imperative that Neotropical systems are given the same scholarly attention that their well-studied cousins within other regions have received. This will provide more information to the importance of Neotropical wetlands in regards to economic worth, current carbon sequestration efforts and for human subsistence, use, and resource extraction in the future.

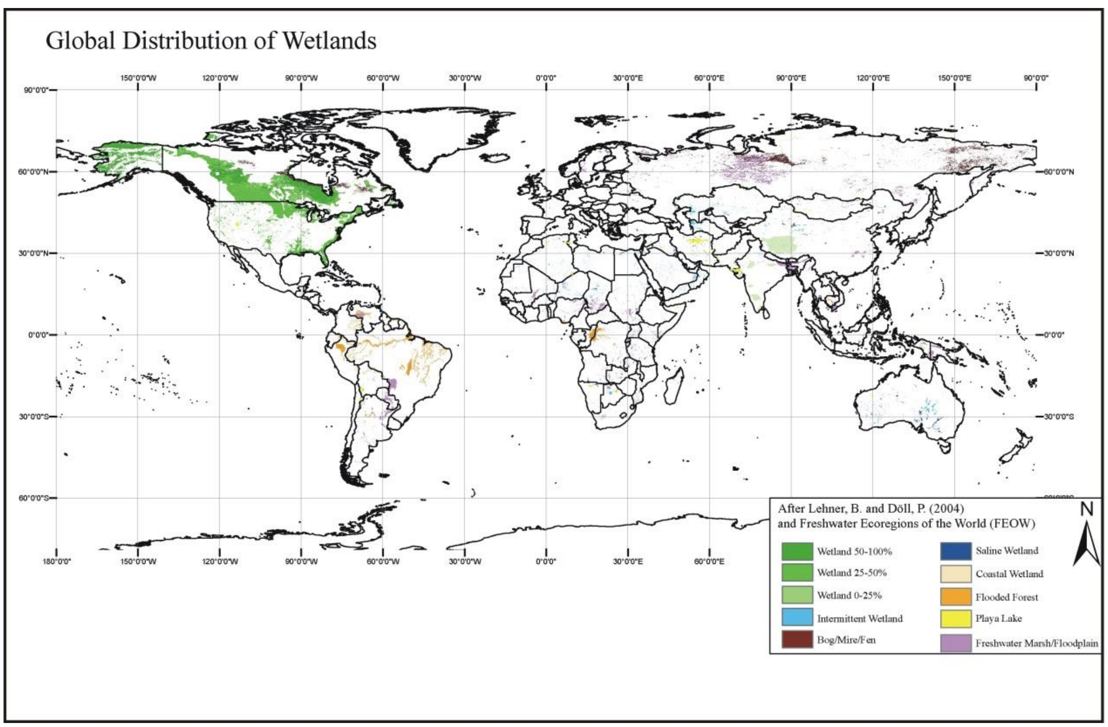

Figure 1.1. Global distribution of wetlands.

Through this work I strive to provide new and innovative understanding of anthropogenically manipulated wetland agricultural systems within case study sites in the Maya Lowlands of northwestern Belize. My dissertation is fueled by over forty years of wetland study in the region (Siemens and Puleston 1972; Puleston 1978; Adams et al 1981; Turner and Harrison 1981; Pope and Dahlin 1989; Jones 1994; Dunning 1996; Baker 2003; Beach et al., 2009; Beach et al., 2015a and 2015b), but also through new geoscience and remote sensing techniques that had yet to be applied in this region. I am providing new long-term records of wetland environments using multi-proxy geoarchaeological methods that can then be linked to larger regional paleoclimatic models for the Maya Lowlands. This research is organized and explored through the dissertation by the following research questions organized into four research themes (T1-T4):

- **T1: Past Human/Environment Systems over Time**

  What are the best ways to systematically reconstruct wetland paleoenvironments and anthropogenic manipulation within case study sites in northwestern Belize?

  To what extent can empirical science better detect human manipulation and modification of these wetland environments, especially in time periods of cultural and environmental transition?

  How can we be sure what is natural versus human in these landscapes?

- **T2: Past Human/Environment Systems over Space**

  Is this sample size representative of larger complexes of ancient agroecosystems?

  What are the connections or comparability between water and soil and agricultural systems in these areas?

- **T3: Quantification**

  How can remote sensing/GIS be best used to quantify the scale of anthropogenic manipulation and natural geomorphology within these wetlands?

  How can geoarchaeological and paleoecological research complement remote sensing?

- **T4: Merit and Impact**

  How can this research benefit and inform conservation and restoration efforts of wetland systems in the Americas and world?

In order to address these four research question, I have designed an approach that combines geoarchaeological, paleoecological, and GIS techniques to define the three dimensional typology of wetland field in different environments in the Maya Lowlands. I test this new typology with similar research strategies of previous researchers that have conducted geoarchaeological work in the Maya Lowlands, such as soil trenches within known agricultural areas and wetland sediment core sampling. LiDAR (Light Detection and Ranging) provides the first accurate rendering of this wetland landscape and the new cores can be reflect the spatial diversity, which will help improve the data and models developed under earlier tools.

I build my work on the emerging evidence of geomorphological, paleoenvironmental, and geoarchaeological research conducted in the Maya Lowlands and neighboring regions. The primary source of information from these wetland sites comes from archaeological efforts, soil catena surveys, and multiproxy excavation both on and off anthropogenic features within wetlands in the Maya Lowlands. These previous studies provide baseline for soil development, wetland genesis and morphology, and any anthropogenic and natural signatures over the landscape. Previous studies hypothesized that these environments show human adaptation and resilience against environmental change but ultimately failed in the Classic (Pohl et al., 1996) or Terminal Classic (Luzzadder-Beach et al., 2012). By better characterizing the extent and the natural and cultural history of these wetlands, I can provide broader evidence for or against the human resilience and the time of failure hypothesis. This improved trajectory for formation will clarify human wetland interactions and reasons for conservation and paths toward better restoration. Research conducted in these case study zones will provide new data sets that can aid future efforts to quantify and visualize history of wetlands for archaeological, biogeographical, or land management and conservation projects, especially within critical wetlands habitats worldwide.

The intellectual merit of this project is that it creates a new area of knowledge and develops new applications of methods. The results of this work contribute scientific information on environmental change and human interaction that is ongoing in the Maya Lowlands of Central America. Through this research I use new applications of LiDAR to map and analyze ancient wetland agricultural systems. This is a groundbreaking new dataset for the region and provides cutting-edge information to a consortium of archaeologists, geographers, geologists, and biologists that have worked in this region for over 30 years.

Outreach and scientific communication have been important outcomes and broader impacts of my work. Throughout the course of my research I provided opportunities for three undergraduate laboratory assistants to aid me with all data processing and laboratory work from 2015-2018. This provided three University of Texas undergraduate students with a unique opportunity to engage in advanced laboratory analysis and co-author subsequent peer-reviewed journal publications.

In addition to this, I have developed a series of laboratory exercises based on my research that are geared towards grades 9-12 students in collaboration with the public school system in Austin, Texas as part of the Scientist in Residence program at UT-Austin's Environmental Science Institute. By disseminating a series of laboratory exercises based on my research, Earth and Space Science students have developed an understanding of cultural heritage sites and critical wetland landscapes, promoting sustainable management and conservation. This outreach provides an educational opportunity for those students who may be interested in pursuing a career in geoarchaeology and similar fields.

1.2 A Review of Wetland System Science

The study of wetlands is encompassed by many traditional disciplines, especially ecology, geography, and pedology. Other disciplines, like archaeology, recognize the need for understanding wetlands as a distinct environment that affects preservation of cultural materials in specific ways. Wetland systems are best studied in an interdisciplinary fashion, as they are inherently complex landscapes.

The definition of wetland is simple, even if the system itself is not. A wetland is defined as a landscape that is saturated with surface or groundwater, or some combination of the two, for at least some time during a year, such that the soil is waterlogged during variable periods depending on the wetland type. This addition of water is such that it creates an ecology and pedology that is distinct from the surrounding regions. Wetlands combine attributes of terrestrial systems and aquatic systems both in regards to soil and biology, and are as diverse or perhaps even more diverse in classification as any other geographic region. Due to the diversity of wetland types across the world, scholars have struggled in adequately describing wetlands and determining the upper and lower limits of the definition. This is because wetlands can be located anywhere that there is sufficient water storage for saturation either seasonally or perennially, and therefore they are diverse in scale, biology, and use for human populations.

Wetlands have been critical geographic place throughout the deep time of the history of Earth. Geologically, the fossil record demonstrates wetland environments to have appeared as early as the Paleozoic (Greb et al., 2006). The first evolutions of land plants, occurring in the Late Ordovician or Early Silurian were certainly transitional species like mosses, lichens, and pre-vascular plants that lived on wet mineral rich sediments before branching out into true terrestrial zones. By the middle of the Devonian, the fossil record shows marshes and swampy proto-forests that allowed for the terrestrialization of many arthropods (Greb et al., 2006). Since their early development, hydric environments have acted as biodiversity zones and places of refugia during global climate fluctuations. Much scientific research has been conducted on paleo-wetlands, mostly due to their economic value, as their facies are often zones of coal, shale, and other important resources. Examples of this include the coal-bearing deposits of the Carboniferous Period. Throughout Earth’s history wetlands shrink and grow, driven by plate tectonics and climate forcing. The modern spatial distribution of wetlands arises from global change during the Pleistocene and the Holocene, and has been modified further due to the rise of the Anthropocene. In the temperate and boreal regions of North America, Europe, and Russia, many hydric landscapes developed about 18,000 years ago, during deglaciation after the Last Glacial Maximum. At this time, global temperature increases and retreat of the ice sheets led to landscape and ecosystem rearrangement, leading to widespread peatlands, fens, and bog formation. Nearshore wetlands were dynamic through the late Pleistocene as sea level was rising and flooding shores as well as creating new coastal wetlands in land. This started to stabilize globally in the mid Holocene but the slower late Holocene sea level rise continued to create more wetlands inland on flat coastal plains as around the Yucatán. Climate variability also influenced water availability during the Pleistocene and Holocene. For example, wetland patterns shift over long time scales within Africa and Southeast Asia due to the migration and strength of the Inter-Tropical Convergence Zone (ITCZ) and the development and collapse of monsoonal systems (Sinha 2011, Shanahan et al., 2015). Wetlands in many parts of Africa today are sustained through seasonal and extra-annual flood pulses, as in the case of the Okavango Delta in Botswana (Milzow 2009).

The diversity, function, and form of wetlands is controlled by hydrology, geomorphic agents, soil types, and biologic agents, which are in turn controlled by larger scale drivers such as underlying geology, overall climate, and anthropogenic forcing (Figure 1.2) Hydric systems of various scales can occur in high altitude mountains, low-lying deserts, within forests, and along coastlines. This diversity of size and type of wetland has been internationally recognized and classified into the following categories following the historic Ramsar Convention of 1971. The Ramsar Convention has classified the following: 12 Marine/Coastal types of wetlands, 20 types of Inland wetlands, and 10 types of Anthropogenic wetlands. Despite these efforts, wetlands are still difficult to quantify and map, even with advanced remote sensing techniques. This is due to human use, manipulation, and destruction of wetland systems and due to the natural hydrological fluctuations and pattern changes both seasonally and annually. Wetlands are rarely if ever a stable state, as hydrological inputs and outputs within these systems fluctuate on multiple scales, from seasonally to over the course of millennia.

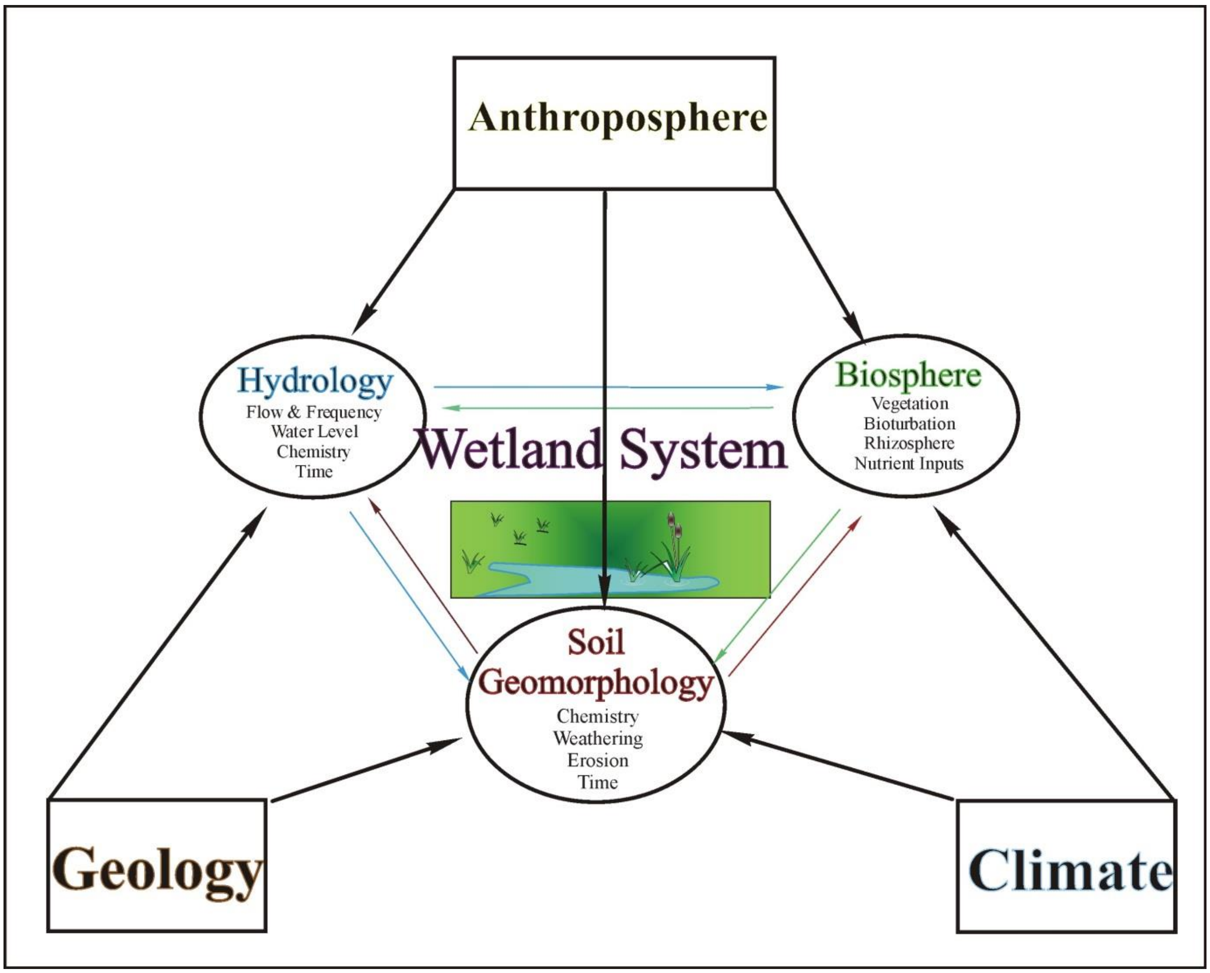

Figure 1.2. Wetland System Science as a comprehensive diagram.

Despite current and ongoing research within natural and anthropogenic wetland systems in the Maya Lowlands of Belize, Guatemala, and México, few of these systems have been mapped and recognized by global wetland databases, and thus cannot be taken into account in large scale studies on carbon sequestration and climate modeling (Figure 1.3). The inherent natural fluctuations within wetland systems adds complication to research and conservation, especially over long scales and for forecasting future fluctuations and the cost effectiveness of such efforts. These systems are in general understudied within the natural sciences due to a variety of factors, including the difficulty of undertaking fieldwork within them, the general discomfort of working around them, and their lack of charisma and poor representation throughout media and culture (Mitsch and Gosselink 2015).

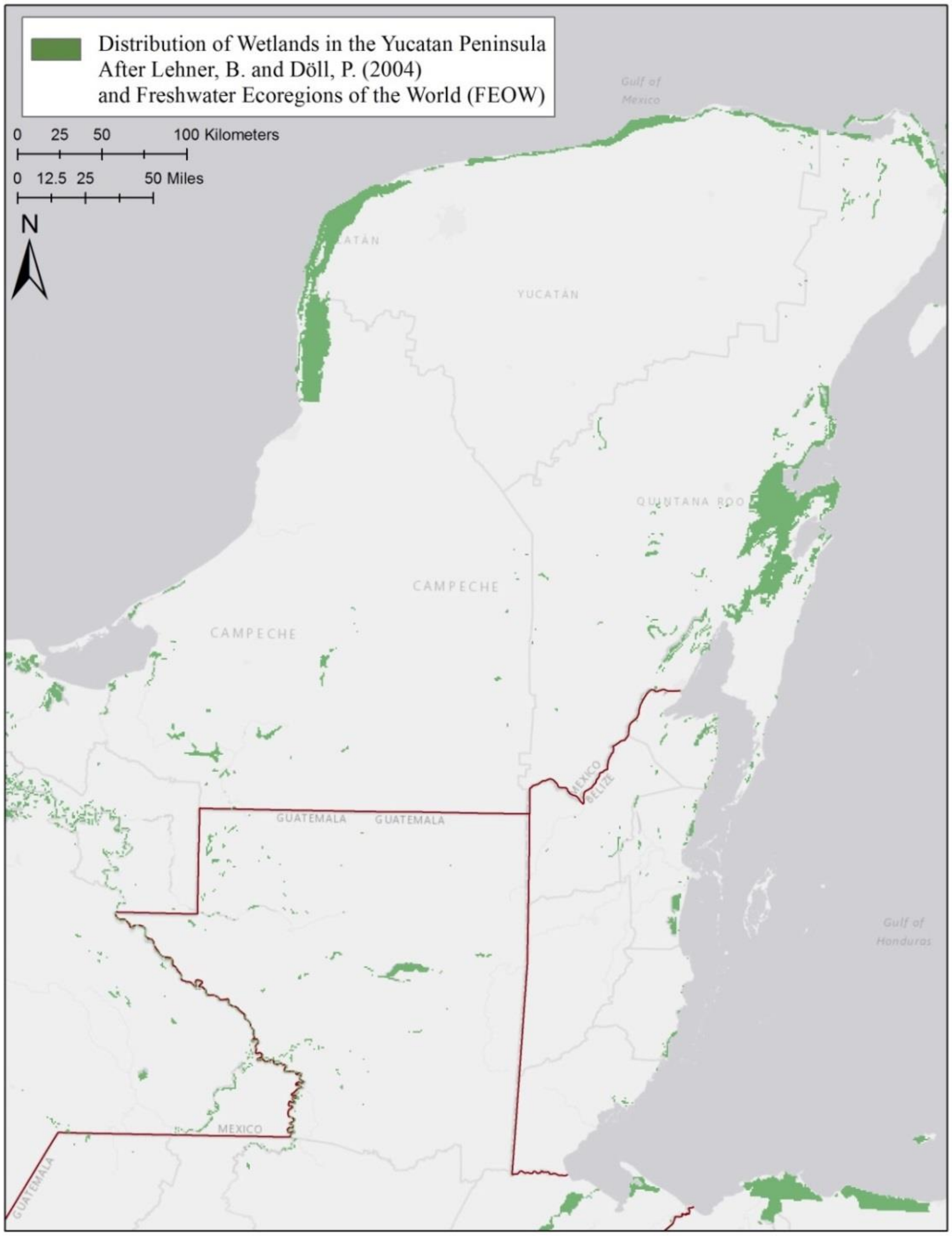

Figure 1.3. Current global estimation of wetlands in the Maya Lowlands region.

Despite all of this, wetlands have proven time and time again that these systems are critical for humanity. Human interaction with wetlands is as old as *Homo sapiens* and occurs across a variety of spatial scales, including the global humid tropics, high latitude and high altitude peatlands, and intermittently flooded drylands of Africa, the western Americas, and the Middle East. In the Azraq basin of Jordan, geoarchaeological evidence suggests that human-environmental interactions in wetlands occurred as early as 23,000–17,400 years BP (Ramsey et al., 2015). The ancestral floodplains of the Tigris and Euphrates rivers show evidence of human settlement and anthropogenic modification over the entire course of the Holocene (Jotheri et al., 2016), as do today's critically threatened al-Ahwar mudflats, floodplains, and marshes of Southern Iraq, where these great rivers conjoin (Stevens et al., 2009). Across the Americas, indigenous groups have used wetlands as a vital source of materials and food production (Beach et al., 2012). Clovis culture occupied spring fed wetlands in the Great Plains and the desert Southwest of North America as early as 11,600-11,000 years BP (Holliday 2009). Wetlands were essential components to crop domestication throughout Asia. Along the Yangtze River in China, wetlands became tools for rice production as early as 7000 years BP, which quickly spread to many other parts of Asia, such as the Korean peninsula between 4000-5000 years BP (Lee et al., 2014; Silva et al., 2014).

Currently, wetland loss across the planet is occurring at a crippling rate. Some research compares the rates of wetland loss to be as rapid as the rates of rainforest loss across the globe (Ellison 2004). The Convention on Wetlands of International Importance, conducted in 1971 in Ramsar Iran hypothesizes that approximately 87% of global wetlands have been lost since AD 1700. This loss has accelerated since AD 1900. These losses come with a high cost. As wetland area declines, so does the monetary value of the ecosystem services that wetlands provide. Costanza and coauthors (2014) theorizes that almost $10 trillion USD has been lost due to decline in wetland area from 1997 to 2011.

Wetland restoration is complex, expensive, and needs a great deal more research and collaboration between scientists and engineers to be successful at a large scale. This perfect storm of complexities is why research on human-environment wetland interaction over the course of the Anthropocene is such a critical topic of focus. Now more than ever it is necessary to understand and quantify the value of global wetlands, especially due to current global issues such as food security, sea level rise, biodiversity, and production and sequestration of climate relevant gasses (especially $C0_2$ and CH_4). Wetland conservationists from all disciplines agree that these systems provide valuable habitat and ecosystem services. Further, archaeologists, historians, and geographers agree that hydraulic civilizations across the world have managed and utilized hydric landscapes for millennia.

Although wetlands are rarely, if ever, in a stable state, they often serve as extremely productive zones for studying paleoenvironmental change and human use over the *longue durée* due to their geomorphology and geochemistry (Hill and Holliday, 2011; Walsh et al., 2014, Ramsey et al., 2015). Wetlands are often aggrading landscapes, and their typically low-oxygen conditions provide good preservation for many paleoenvironmental proxies such as microflora and microfauna. This, combined with their persistence as an intensively anthropogneically modified landscape across cultural and histories, make them an excellent venue by which we can explore Holocene landscape change, the concept of the Anthropocene, as well as conservation, terrestrial carbon cycling, and climate relevant gas emissions in a rapidly changing world.

1.3. Human Resilience Theory and Wetlands

One concept that scholars have long employed is the wetland as “persistent place”, or rather, one that human settlement continues to occupy and alter through climate shifts and cultural change (Ramsey et al., 2015). Humans have a complex and long lasting relationship with wetlands that runs deeper than modern perceptions. This research is informed by a theoretical framework that encompasses human ecology, adaptive strategies, and the concepts of cultural collapse/resilience, explored extensively by Karl Butzer (1983, 1989, 2008, 2012) as well as the theory of adaptive change (TAC), which is based off of archaeological resilience theory (Redman 2005) and has been further developed by Arlene M. Rosen and Isabel Rivera-Collazo (2012). This theory suggests that the relationship that past cultures have had with environments can provide a window by which contemporary society can understand resources demand and ecosystem management (Redman 2005).

Butzer’s work on adaptive systems and strategies spans several decades of research across a multitude of cultures and time periods and refers to the capacity a society has to change and adapt to various environmental stressors. In his research on human ecology, Butzer explores, using many case studies, the ways in which civilizations are able to rearrange and recreate natural settings, often on large scales, in order to suit their purposes, often at a scale and complexity that surpasses most organisms on the planet. We can understand and assess these landscape modifications using geoarchaeology (Butzer 1982). Adaptive transformation, changes in social behavior, technology and resource utilization, and such changes have regional or global repercussions for subsistence, settlement, and demography (Rosen and Rivera-Collazo 2012). In-depth geoarchaeological research provides us with a deeper understanding of both anthropogenic manipulation and climate change influences on wetland environment, development, and persistence (Luzzadder-Beach et al., 2012). Such an understanding can allow for greater insight into management strategies for current efforts in wetland protection and restoration.

1.4. DISSERTATION OVERVIEW

Chapter 1 discusses all the questions and theories that drive this dissertation. Chapter 2 provides a very broad background of Central America and within it, the cultural and geographic region we know as the Maya Lowlands. It is in Chapter 2 that I review the region's general geology, climate, soils, and ecology. Subsequent chapters (3, 4, 5, 6) consider more detailed explanations of each of these systems (place-specific geology, environment, soils, and ecology) as they relate to my case study areas. I also review the methods that I used throughout the dissertation in detail within Chapter 2, including field and laboratory work, uncertainty, calibrations, standards, and validation of data sets used later within the different case study zones. Chapters 3 is a review of remote sensing techniques I used to understand the spatial part of my geoarchaeological and paleoenvironmental work, and provides a quantitative and large scale analysis of agricultural features detected within my case study zones. I first published Chapter 3 as the lead author in an edited volume in 2016 entitled *Changes in Latitudes, Changes in Attitudes: Transitions and Thresholds throughout Central America and Beyond*, published by the Center for Archaeological and Tropical Studies Occasional Papers, University of Texas, Austin. The current Chapter 3 also includes additional data from the Northwestern Belize LiDAR Consortium's acquisition of a LiDAR data set in the summer of 2016. Chapters 4, 5, and 6 all focus on different case studies that I use to answer my research questions.

Chapter 4 focuses on fieldwork conducted in 2011 and 2015 in the wetlands of Chan Cahal, Neundorf, and Sierra de Agua. The research on these wetlands provides a regional understanding of anthropogenic modification over time and space. Chapter 4 is (as of spring 2018), under review in the Journal *Quaternary International* as part of a special issue entitled **Landforms and Palaeosoils**. I am the primary author and primary data analyst for this publication. I wrote most of the paper and I sampled soils, and analyzed them for a suite of geochemical proxies, including elemental geochemistry, stable isotopes, and organics .Coauthors and their roles on this publication are as follows: Timothy Beach, Sheryl-Luzzadder-Beach are experts in the region and provided support for fieldwork and fieldwork design. They also serve as PIs for funding sources, lab facilities and permits. Timothy Beach also provided writing, soil interpretations, and editing of the manuscript. Fred Valdez and Tom Guderjan serve as PIs for permits and gave minor edits, and Colin Doyle and Sara Eshleman served as field assistants and secondary data analysts for the publication. Steve Bozarth provided pollen analysis.

Chapter 5 focuses on fieldwork conducted in the summer of 2014, and provides analysis of wetland cores extracted from the northern most portion of the Birds of Paradise wetlands on the Rio Bravo Floodplain. The cores provided samples that I used for paleoenvironmental proxies for both natural and anthropogenic change over time. The majority of this chapter has been reworked into a publication that is currently (as of spring 2018) under review in the journal *Geomorphology* as part of a special issue entitled **Human Impacts on Geomorphic Systems and the Legacy Karl W. Butzer.** I am the primary author and primary data analyst for this publication. Coauthors and their roles on this publication are as follows: Timothy Beach and Sheryl-Luzzadder-Beach, who helped me implement the fieldwork design for the 2014 season and are the PIs for funding sources, lab facilities and soil permits. In addition Timothy Beach provided edits for writing and analyses. Duncan Cook served as an editor for methodology, and provided analysis for magnetic susceptibility. Gerald Islebe and Manuel Palacios-Fest served as pollen and microfossil consultants, respectively and produced these datasets within their laboratory facilities. Colin Doyle and Sara Eshleman served as field assistants and secondary data analysts for the publication. Fred Valdez and Tom Guderjan serve as PIs for archaeological permits and gave minor edits.

Chapter 6 focuses in on reconstructing the Birds of Paradise wetlands, the largest (so far) continuous swath of anthropogenically modified hydric landscape within northwestern Belize. This chapter details the fieldwork conducted in the 2016 and 2017 field seasons, and focuses on geoarchaeological methodology to determine the timing and duration of human impact on the system. It is my intention to rework this chapter into a publication that will be submitted to a physical geography journal by the summer of 2018, in which I will be the primary author with similar co-authors. Chapter 7 summarizes and concludes this research and provides a review of the value of global wetlands and a critique on the current research on conservation and reclamation of wetland landscapes. In this final chapter, I provide insight on the state of Neotropical wetlands in the Americas in the face of global anthropogenic climate change, the value of these wetlands as biodiversity zones and carbon sinks, as well as resource rich cultural heritage sites the people of Northwestern Belize. I also review policy and preservation of Neotropical wetlands in the Americas as we look forward to the future of agriculture and conservation within the Maya Lowlands.

Chapter 2: Human Use of Wetlands in the American Neotropics

2.1. A Review of World Wetland Agriculture

Wetlands are sources of water and other resources, and therefore are a choice persistent habitation both in the past and in modern times. The most prominent agricultural systems on earth developed in the wetlands of central and southern Asia and are arguably the primary crop producing engine for humanity in the modern world. Wetland agriculture along the Yangtze River in China was essential for the domestication of rice as early as 7000 years BP, which quickly spread to many other parts of Asia, such as the Korean peninsula between 4000-5000 years BP (Lee et al., 2014).

Within the Middle East, the ancestral floodplains of the Tigris and Euphrates rivers show evidence of human settlement and anthropogenic modification over the entire course of the Holocene (Jotheri and Allen, 2015; Jotheri et al., 2016,), as do today's critically threatened al-Ahwar mudflats, floodplains, and marshes of Southern Iraq, where these great rivers conjoin (Stevens 2007; 2009).

In the islands of the Pacific Ocean, wetlands provide refugia for various populations, as well as zones for intensive agricultural production. Taro (Colocasia esculenta) was the main crop for cultivation within Polynesian systems, and the crop was cultivated through the use of raised beds and rectilinear drainage systems within swamp systems (Kirch and Lepofsky 1993). Swamps were zones of settlement as well as agriculture, as Māori pā (villages) dating to ~AD 1500 have been located around lakes and swamps, and archaeologists in this region consider swamp pā to be typical rather than marginal settlement zones for this culture and time period (Irwin 2013).

Springs and playas in the southwestern regions of North America often contain evidence of human occupation, especially by the Clovis culture, was in place by 11,600 years before present (Holliday 2007), and in some locations even as early as ~13,000 years before present (Sanchez et al., 2014) These playas, such as Blackwater Draw, are now only intermittently moist but contain buried layers of dark organic sediments representing a marshy paleoenvironment as well as evidence of resource exploitation and large game butchering (Haynes 1995). Paleo lakes of the American Southwest were persistently occupied by Paleoindian populations through droughts, as is evidenced by the long-term occupation of sites such as Lubbock Lake in Yellowhouse Draw on the High Plains of Texas, in which cultural deposits date back to 11,000+ years and continue through at least two severe middle Holocene droughts, moving forward into Protohistoric and Historic cultural deposits and into modern times (Holliday 1985). Tidal wetlands, floodplains and estuaries were exploited for a variety of resources in what is now Florida as early as 7200 cal B.P., though earlier sites probably exist but are currently inundated due to rising sea level throughout the region (Saunders and Russo 2011). Throughout North America, prior to European invasion, scholars hypothesize that there were at approximately 221 million acres of wetlands, but as of the mid-1980s, only about 103 million acres remained (Dahl and Johnson, 1991), which is due primarily to widespread draining in pursuit of their nutrient rich soils and prime agricultural lands. In the 1700s, much of the seasonally and permanently flooded portions of what was to become the southern states of the U.S. had been drained, channelized, and diverted for large scale plantation use (Beauchamp 1987; Dahl and Allord, 1996), and as colonialization continued to spread westward, so did the intensive agriculture into regions such as the Ohio and Mississippi River Valleys, the bottom lands of Missouri and Arkansas, the prairie pothole wetlands of the western states, and into the Central Valley of California (Dahl and Allord, 1996).

2.2 Neotropical Wetlands

Although we have many studies of wetlands from temperate regions, there are still too few studies of tropical wetlands (Marín-Muñiz 2014). This lack of research hampers our knowledge of local ecosystems, anthropogenic manipulation, and our ability to model global changes such as greenhouse gas fluxes and climate dynamics. Here I review the current literature on natural wetland formation as well as anthropogenic manipulation throughout Neotropical Central America. I also provide a geologic and geographic setting for my case studies from the Maya Lowlands of Belize.

As a geographic setting, wetlands have been difficult map, model, and synthesize. This is because wetlands are often in a state of flux or transition by nature. We can define a wetland as terrestrial setting that is characterized by shallow water and saturated conditions for at least some portion of a calendar year. These systems are also characterized by unique soils and adapted vegetation. Temporal scales, climate, hydrology, physical/chemical environment, and biota are all components of a wetland at any scale, and there are significant feedback loops, both negative and positive, between these various components that make up a wetland that dictate the relatively stability, instability, and fluxes that occur within the system. Wetlands can therefore be as ephemeral and patchy as the playa lakes or prairie potholes of the American west, or as widespread as the peatlands of Siberia. Out of all the wetlands on Earth, some of the most poorly understood and understudied among them are those located in the global south. The American Neotropics is one such region in which wetlands are poorly understood.

Ellison (2004) classifies Neotropical wetlands within Central America as 5 unique ecological systems. Combined, these systems cover about eight percent of land area at about 40,000 km^2 (Ellison 2004). These systems are of particular importance for the region and there has been little research attention given to them throughout scientific and management communities.

2.3. Case Studies in the Wetlands of the Maya Lowlands

The Maya Lowlands has provided researchers with over 30 years of case studies within low-lying wet environments, the long occupational sequences from this region, coupled with the various forms of natural wetland environments, provide an excellent lens by which we can understand human-wetland interaction over the *longue duré*. Although this region has been researched for over three decades, there is still much to be answered regarding regional climate, wetland development and form over the Holocene, and human use and interaction with wetlands as a critical resource.

The Maya Lowlands is a cultural and geographical province of northern Central America that extends through parts of Guatemala, México, and Belize. To understand this distinct region we need to fully understand the geological and climatic framework of Central America. We can then use this as scaffolding by which we can interpret the biogeography of the region as well as and inform our understanding of cultural heritage and agroecosystems.

2.3.1 Geology and Soils of the Maya Lowlands

The Central American subcontinent that divides the Pacific and Atlantic Ocean basins by a narrow isthmus. The major tectonic plates that affect Central America include the North American Plate, the Cocos Plate, Nazca, and the Caribbean plate. Active orogeny in the Cenozoic occurred between the Cocos and Caribbean plates at the Middle America subduction zone as well as sinistral shearing and faulting between the Caribbean and North American plates (Marshall 2007).

Due to these varied physiographic complexities, Central America has a considerable amount of topographic relief and a significant precipitation gradient. This gradient in turn leads to dramatic and intensive climate and ecosystem fluctuations across the entire landscape (Karmalkar et al., 2011). México's portion of the Yucatán Platform is largely low lying and karstic. Generally, soil suites form on Cenozoic marine carbonate rocks, similar to the composition of northwestern Belize. In the northern portion of the Yucatán Platform, a distinct half-ring of karstic sinkhole features (cenotes), signifies a large concentric band of permeable karst limestone. This structure overlies the famous Chicxulub impact crater that designates the termination of the late Cretaceous (Marshall 2007).

2.3.2. Climate of the Maya Lowlands

Multidecadal and interannual climate variability within the Maya Lowlands has been an increasingly considered topic, mostly due to the interdisciplinary interest of understanding the Central American megadroughts and their effect on human populations and cultural transformations within the region. Climate archives of Central America have mostly been generated over the past 40 years from lake sediment records and from speleothems, and current climate research focuses on precipitation patterns and the driving mechanisms behind these rainfall patterns.

The modern climate of Central America is generally classified as a tropical wet/dry system The primary Köppen-Geiger climate types in the region include the following: tropical rainforest (Af) to tropical monsoon (Am), tropical savanna (Aw), and hot semi-arid steppe (Bsh) (Sekhon et al., in prep). The general rainfall pattern consists of a wet season from May through November driven by convective systems (Sekhon et al., in prep). The ultimate driving mechanisms of regional precipitation include the seasonal placement of the Intertropical Convergence Zone (ITCZ), the easterly trade winds, subtropical low/high pressure dynamics, and extratropical cyclone events (Gamble and Curtis 2008). For the rest of the year the region in general exhibits a pronounced dry season. There has been some research on the timing and importance of a bimodal midsummer dry period or drought (MSD) within Central America. This MSD event occurs over the Caribbean roughly during the month of June and is the subject of study for modern problems such as agriculture at local scales and for larger regional climate change models (Gamble et al., 2010).

Other climate mechanisms of interest for this region include interannual events such as El Niño-Southern Oscillation (ENSO), which is a coupled atmosphere/ocean oscillation. This variation occurs in winds and sea surface temperatures over the tropical eastern Pacific ocean that cycles with a duration of two to seven years, and has implications for the climate of the global tropics and subtropics. Other mechanisms on a multidecadal scale include two-low scale frequency climate variabilities, the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). The PDO is a pattern of climate variability that is centered over the mid latitudes of the Pacific, affecting both the ocean and atmosphere, and the AMO is a cycle of sea surface variability in the North Atlantic (Schlesinger and Ramankutty, 1995).

Our general understanding of paleoclimate and ecological trends (Figure 2.1) comes from through long-term and nearly global scale records such as the Greenland ice cores (Dansgaard 1993) and the Cariaco Basin record (Haug 2001) and a handful of regionally specific speleothem and lake core records (Hodell et al., 2008, Douglas et al., 2015). These records demonstrate that the Late Glacial Maximum was drier than conditions today. Moist conditions generally prevailed after the LGM until the drying and cooling of the Younger Dryas. Hodell’s 2008 paleolimnological work provides a record of pollen and alternating lake sediment layers that are tied to broad climate shifts in the Cariaco Basin. They contradict previous records by interpreting relatively cool and moist conditions in the region during the Late Glacial Maximum and characterize the vegetation as montane pine-oak forest. After 18,000 years before present, paleolimnological studies interprets dry conditions in this region (Hodell et al., 2008).

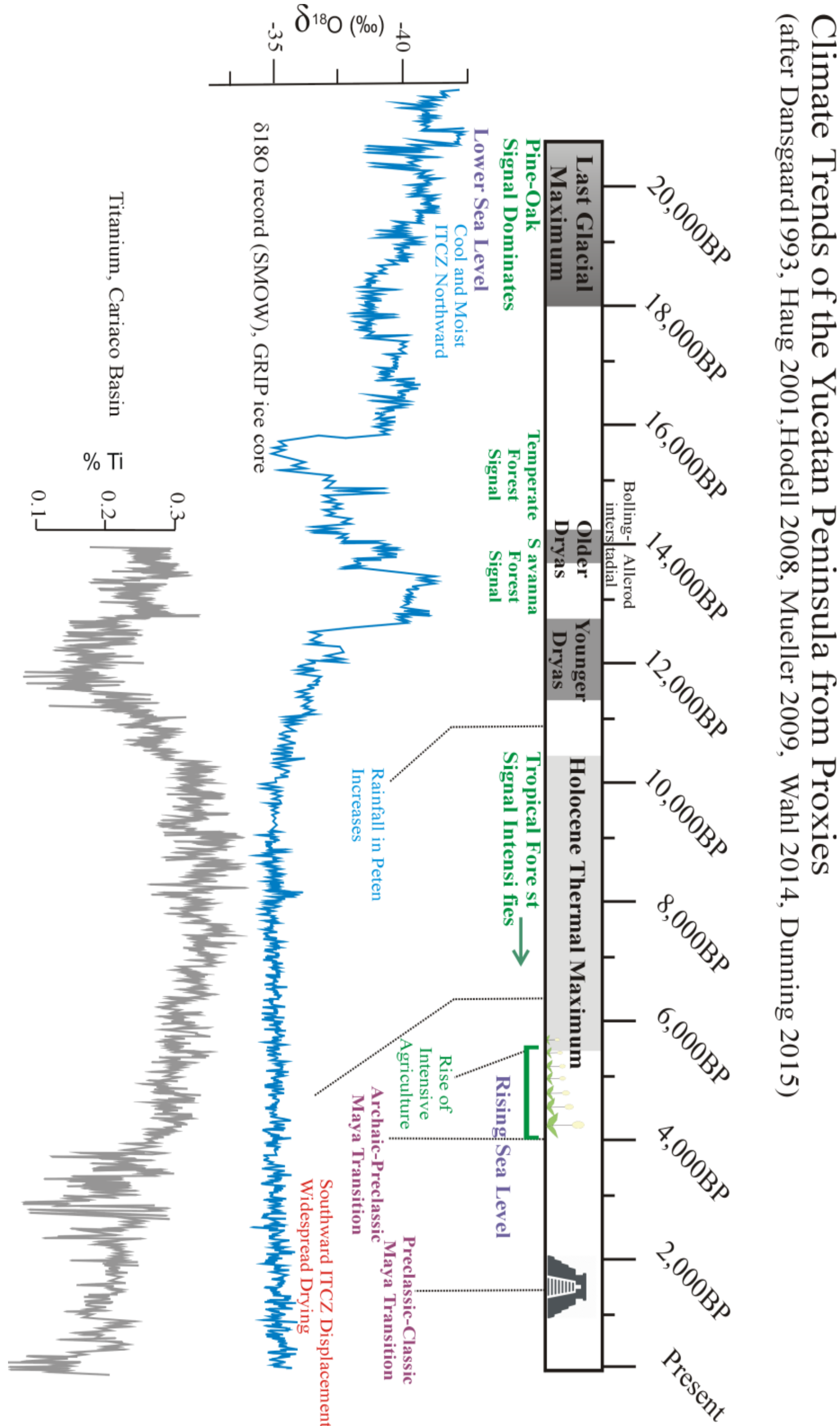

Figure 2.1. Climate Trends in the Yucatán Peninsula.

Paleoclimatological studies suggest that in general Central America began to warm and become more humid during the *Bølling-Allerød* warm period (14,700-12,700 years BP). At this point, pollen records reflect widespread temperate forests in the Petén and across the region (Wahl et al., 2014). At the start of the Younger Dryas, there is again evidence for drier conditions and savanna pollen assemblages. After the Younger Dryas, conditions get wetter and remain wet and warm until the mid-Holocene except for short-term cooling and drying events such as the 8.2 k Heinrich event. Upland forests of the Maya Lowlands became tropical and the intermittent *bajo* wetlands became wetter with a few perennially wet pockets, and pollen studies suggest that the ecological composition of the region shifted as well (Dunning et al., 2015). Following sea-level rise during the Holocene, the low-lying coastal plain became inundated along lower stream valleys within depressions and lagoons (Beach et al.,2009).

2.3.3. Ecology of the Maya Lowlands

There are several distinct vegetation zones that generally follow the topographic relief. Coastal regions are dominated by mangroves (*R. mangle*, *A. germinans* and *L. racemose*), sedges, and cattails. Savanna regions are generally rich in palm, pine, (*Pinus spp)* and oak, (*Quercus spp),* dominated by *Quercus oleoides*, but up to nine other species have been identified in Belize (Balick et al., 200) as well as many grass species. The riparian forested areas and the upland forests on the escarpments are the most biodiverse, and are dominated by broadleaf trees and shrubs. Some of the more well-known trees include ceiba (*Ceiba pentandra*), Trumpet Tree (*Cecropia obtusifolia*), figs (*Ficus spp.),* and ramon (*Brosimum alicastrum*) (Brokaw and Mallory 1993; Bhattacharya et al., 2011). There is an extensive and still growing body of literature that grapples with the use of plants throughout history in the Maya world, especially intriguing for this particular study is the ancient Maya use of specific wetland environments, such as upland *bajos*/*rejolladas* (intermittently wet karst sinks) as microclimates for specialized crops (Munro-Stasiuk et al., 2014).

2.3.4. Culture and Wetland Heritage in the Maya Lowlands

Humans have influenced the geography of Central America for 10,000 years (Table 2.1). A variety of groups and cultures have occupied all reaches of this region and developed a wide array of agricultural techniques, but the focus of this research is that of the Maya. The Maya people have been noted as an influential culture, and their urban planning, writing style, artwork, mathematics, and astronomy is an important subject of study in history, archaeology, and anthropology. Increasingly, archaeological evidence suggests that Classic Maya in particular, who occupied this region until roughly AD 900, also intensively manipulated, sustained, degraded, and revivified their wetland environments at different times through a variety of soil and water management strategies (Baker 2003; Beach et al., 2009; Guderjan 2007; Guderjan et al., 2009; Beach et al., 2015). Currently, wetland research in the Maya world focuses on where and when wetlands were modified into canal and field systems, what kinds of agricultural practices occurred in them, and the relationship that these wetland systems have with cultural growth and abandonment, as well as climate factors such as drought cycles.

At present, there are over six million indigenous Maya people throughout the world, though throughout both historical and modern times indigenous Maya groups have suffered greatly from European invasion and modern conflict and war. Colonialism and globalization have greatly damaged indigenous peoples as well as indigenous land practices. By understanding and classifying Central American wetlands as zone of cultural and biological heritage and importance, it is possible that in the future they will receive protection that could benefit indigenous communities that live in and around them.

Table 2.1 Cultural Periods and Transitions of the Maya.

Cultural Time Periods of the Maya (after Beach et al., 2008)			
Years BP	**Years BC/AD**	**Cultural Period**	**General Human-Environment Patterns**
9000+	8000 BC +	Paleoindian	Hunter-gatherer
9000-4200	8000 BC-2000 BC	Archaic Period	Stone tools, early agriculture
4200-3000	2000 BC-1000 BC	Early Preclassic	Agriculture, deforestation
3000-2400	1000 BC-400 BC	Middle Preclassic	Agriculture, deforestation, increased erosion
2400-1850	400 BC-AD 159	Late Preclassic	Agriculture, deforestation, increased erosion, population increases
1850-1700	AD 159-AD 250	Terminal Preclassic	Continued erosion
1700-1350	AD 250-AD 550	Early Classic	Less erosion, population increases, increased agriculture
1350-1180	AD 550-AD 800	Late Classic	Less erosion, population peak, wetland agriculture increases
1180-1050	AD 800-AD 900	Terminal Classic	Wetland agriculture increases
1050-700	AD 900-1200	Early Postclassic	Limited/opportunistic use of some agricultural systems
700-450	AD 1200-AD 1511	Late Postclassic	Reforestation
450-present	AD 1511-present	Colonial/Modern	Reforestation

2.4. CURRENT METHODOLOGIES

This dissertation employs a wide array of empirical methods in order to understand and model change over time, especially changes that were anthropogenically induced. In doing so, I employ both geoarchaeological and geological technique. Some of these methods have been used for many years within the Maya Lowlands. Other methods are well tested in other geographic and archaeological settings, but are still relatively new for this region. Here I provide broad methodological information on all phases of the research within this project. More detailed methodology will be provided in each section as it pertains to the specific components of the research chapter by chapter.

2.4.1. Survey, Mapping and Remote Sensing

Remote sensing is a popular method within many current geographical and archaeological research projects, and has assisted in the detection and subsequent excavation of prehistoric anthropogenic features in a variety of geographic settings across the globe (Parcak 2009). Within the scope of this research, I have used a variety of mapping and remote sensing techniques to pinpoint wetland areas of interest (wetland AOIs) that have the highest probabilities of exhibiting anthropogenic modification and long-term use. Remote sensing also helps to quantify the extent of areas that were used as agricultural landscapes by prehistoric populations. Both multispectral satellite imagery (specifically Geoeye) and LiDAR are used within this research to quantify ancient agricultural features and anthropogenic wetlands. These features were then ground-truthed using Ashtech and Garmin GPS units on pedestrian survey, and then excavated using a variety of pedological and geoarchaeological techniques. We additionally cored wetlands with standing water using a Livingston Corer and then used a variety of paleoecological techniques to get at wetland change over time.

2.4.2. Geoarchaeology

Geoarchaeology seeks to fill a gap between traditional archaeology, geomorphology, and environmental history. Geoarchaeology is a subfield that continues to grow within geography, geoscience and anthropology because of its ability to be cross-disciplinary (Butzer 2008). Geoarchaeologists traditionally consider a variety of proxy data sets, including geochemistry of soils, bedrock, and groundwater, patterns of erosion and deposition, soil quality and organic levels, and various dating methods and techniques to bolster our greater understanding of past societies and how they utilized past landscapes. These data sets contribute to a broader understanding of anthropogenic e manipulation of the environment as well as human response and adaptations to long term climate fluctuations. In this project, I use geoarchaeological methods such as soil pit excavations and soil field descriptions to understand sedimentation and anthropogenic features within soils. I use Loss on Ignition (LOI) to measure both the organic matter and carbonate ($CaCO^3$) content within each horizon of each excavation. LOI is primarily used in archaeology to understand soil formation processes such as deposition and soil development, vegetation growth, wetland development, and can often be correlated with human activity such as agriculture or midden sites (Dean 1974). I use a current adaptation on LOI that is currently used by the National Lacustrine Core Facility (Heiri,et al., 2001) to calculate percent of organic matter and $CaCO^3$ within the soil. This method uses 5g of sediment of dried and homogenized sediment to be weighed into ceramic crucibles. Using a a Cole-Parmer Stable Temp Furnace, samples are first dried at 100°C overnight, and then burned at 550°C for 4 hours, and then again 1000°C for 2 hours. The sample weight is recorded between each burn, and the amount of organic and carbonate content is then calculated using Dean’s (1974) equations:

550°C burn:

$$\%OM = \frac{(pre\ ignition\ weight\ (g) - post\ ignition\ weight\ (g))}{Pre\ ignition\ Weight\ (g)} \times 100$$

1000°C burn:

$$\%CaCO3 = \frac{(pre\ ignition\ weight\ (g) - post\ ignition\ weight\ (g))}{Pre\ ignition\ Weight\ (g)} \times 100$$

This method provides the total organic matter and the total carbonate within a given sample. Most carbonate rich sediments are composed of organic matter, carbonate, and non-carbonate minerals, hence what should be left at the end of the 1000°C burn should be the non-carbonate mineral fraction. However, one drawback of this method is that if a significant amount of clay is present in a non-carbonate material, it could affect the weight loss by 3-4% (Dean 1974). This is due to the fact that many clays contain lattice water that cannot be removed until heated more than 550 degrees (Grim 1953; Dean 1974).

There are other methods that could be used to determine percent organic matter that may not have such an error range within the carbonate stage, such as by determining total carbon content in bulk soil samples and total organic content in acidified soils using a carbon analyzer (i.e. a LECO brand) combusted in an oxygen atmosphere. Any carbon present in the sample is thus converted to CO2, which ten flows into a non-dispersive infrared detection cell, which measures the mass of CO2 present. This mass can then be converted to the percent of carbon based on the dry sample weight. For the purposes of this research, however, since most soils in the Maya Lowlands are primarily carbonate derived, we accept the limitations of the Dean 1974 method and recognize that there could be up to a 4% error within the 1000°C burn portion of this test.

For each case study, I also test the magnetic susceptibility of each soil horizon. This measures the degree to which a soil or sediment can become magnetized. Ferruginous minerals within soils can provide geoarchaeologists with a tool by which we can track environmental changes such as burning events, both natural and anthropogenic, increased biological activity (i. e. the breakdown of organic matter or fluctuations within a wetland environment) or pedogenic processes within a soil (Thompson and Oldfield 1986). Measuring the magnetic susceptibility throughout sediment profiles is a general environmental proxy used to identify whether or not anthropogenic events or soil pedogenesis have occurred over time (Ayala et al., 2007 and Gale and Hoare 1991). In this study, I used both a field magnetic susceptibility meter, and when available, a Bartington magnetic susceptibility meter model MS2 interfaced with a 36 mm internal diameter dual-frequency sensor type MS2B following the procedure outlined in Gale and Hoare (1991). The field meter was a GF Instruments SM-20 magnetic susceptibility meter. In both cases I took the average of three low frequency readings (χ_{LF}) were recorded with an accuracy of up to 0.001.

2.4.3. Geochemistry

The geochemical signal of any given soil can provide researchers with information on its formation processes, parent material, age, and agricultural stability. It can also retain the chemical signature of human use over time. In each case study, I provide baseline geochemistry for each soil pit or wetland core as a proxy for environmental change over time. This information may be indicative of human activity patterns on and around the case study wetlands. A variety of tools can be used to measure the elemental constituents of a soil or sediment.

In past studies, geoarchaeological chemistry studies have focused mainly on a relatively small suite of elements as proxies to infer past anthropogenic changes in the environment. This suite of elements has historically aided geoarchaeologists in site prospection and can indicate activity areas in known archaeological sites (Holliday et al., 1992). In some studies, scientists have analyzed up to 30 elements in soils (Entwistle et al., 2000). The most common tracers studied in archaeology include Ba, Ca, Cu, Hg, K, Mn, P, Pb, Rb, Sr, Th, and Zn (Table 1). Enrichments and depletions of these elements in a vertical soil sequence or across a landscape can aid geoarchaeologists in pinpointing human occupation, activity, and environmental modification in the past. However, this method is still developing within the archaeological geology community. A component that is sometimes lacking within some geochemical archaeology studies is to determine a clear geological baseline for comparison to relative anthropogenic enrichments into a soil system (Matschullat 2000, Oonk 2009). Element mobility and leaching within a soil profile is another consideration that deserves attention (Prohaska 2005), but these are too often not mentioned within archaeological studies. Finally, interpreting anthropogenic soils, even the more obvious *terra pretas* of the Amazon (Glaser et al., 2012), is often highly complicated because of natural processes such as on-site mixing over time, unique background soil chemistry of different regions, and the range of materials that are deposited around anthropogenic landscapes in general (Wilson et al., 2009). Despite these problems, geochemistry continues to play a role in understanding the effects that settlement may have on the landscape (Table 2.2).

Table 2.2. Elements analyzed in past research on soils near/on archaeological sites.

Soil Elemental Signatures Commonly Used in Archaeology		
Element	**Could Indicate**	**Cited from**
Au	Craft production	Cook et al., 2006
Ba	organic waste disposal	Parnell 2002, Wilson 2008
Ca	Agricultural fields	Entwistle 2000, Wilson 2008
Cu	Craft production/mining	Cook 2006
Hg	Craft production/Paint	Parnell 2002, Cook 2006
K	Agricultural fields	Entwistle 2000, Wilson 2008
Mn	organic waste disposal	Parnell 2002
P	organic waste disposal/ market activities	Holliday 1992, Wells 2000, Parnell 2002, Terry 2004, Hutson 2009
Pb	Craft production/Mining	Parnell 2002
Rb	Agricultural fields	Entwistle 2000, Wilson 2008
Sr	Agricultural fields (?) (More often used in bioarchaeology)	Entwistle 2000, Hodell 2004, Wilson 2008
Th	Agricultural fields	Entwistle 2000, Wilson 2008
Zn	Occupation waste/ General production	Oonk 2009, Cook et al., 2006

In this research, I use Mehlich II to isolate and study extractable phosphorous (a proxy for human input in soils) (Oonk 2009). Extractable phosphorus has been used as an indicator of human input (fertilizer) within past agricultural surfaces. Within the Maya Lowlands, P is naturally a limited element within the system, even within wetlands, as it is generally rapidly taken up by the biological community. During prehistoric use within the study area, P was introduced as a fertilizer by human or animal waste, decomposing living organisms, or organic construction material. P will therefore be higher than it would be in the natural phosphorus cycle within buried soils that were agricultural or midden zones. Therefore, in our system, P should build up in archaeological zones that served as trash pits, kitchens, fire residues, and in soils with fertilization. Conversely, P levels may become relevantly depleted in intensively cultivated or cleared areas, where ancient crops might have taken up all the available P in the soil. In this study, I use the Mehlich II extraction procedure for measuring extractable P (Terry et al., 2000), in which 2g of soil from each horizon is dried and homogenized and treated with Mehlich II extractant. The soils are then filtered and the leachette is combined with PosVer reagent. I then used a Hach DR/850 Colorimeter on the % transmittance function at a wavelength of 690 nm (Beach et al., 2017). I then used a standard curve with known P concentrations of KH2PO4 (Potassium dihydrogen phosphate) from which we calculated each sample's phosphorus concentration.

I also used X-ray Florescence (XRF) and Quadrupole Inductively Coupled Plasma Mass Spectrometry (Q-ICP-MS) to provide total elemental profiles (except for light elements such as N, C, and O) for each soil horizon studied. XRF samples were homogenized, powdered, and sieved through a 150 µm mesh screen. Samples were then sonicated into sample cells that hold approximately 1 g of each sample. I used a BTX Profiler to analyze the elemental profile of each sample.

2.4.4. Stable Isotopes

Stable isotopes of carbon and nitrogen are useful proxy tools for reconstructing human impacts and ecological changes in wetland environments in the American tropics. Carbon within inorganic carbonates shows little isotopic fractionation, while the carbon in material derived from plant matter has shown to have varying types of fractionation (Sharp 2007). This is due to differences within plant's photosynthetic pathways that result in the preferential uptake of 12C within C3 plants. There are three general biochemical pathways within global plant communities. The C3 carbon fixation pathway causes C_3 plants shows higher degree of ^{13}C depletion than the other plant communities. Within the C4 and Crassulacean Acid Metabolism (CAM) pathways, the heavier isotope of carbon, 13C is less depleted. The resulting isotope ratios of these plant communities propagate both within soil organic matter and throughout the food chain (Sharp 2007). Past studies of $\delta^{13}C$ values within Yucatán wetland sequences (Beach et al., 2015) have determined that different horizons/human occupations within soils show strong fluctuations between C3 (tropical tree) and C4 (tropical grassland, and in some cases, maize) dominated vegetative communities. Topsoils in the Yucatán are dominated by tropical forest (C3) species while soils that are dated to ancient human occupation in these regions are dominated by C4 grasses, which we recognize to be evidence of forest clearing, the introduction of weedy species, and crop (maize) cultivation.

Fractionation effects will be taken into account within this analysis. Soil organic carbon fractions included microbial biomass carbon (MBC), dissolved organic carbon (DOC), and labile organic carbon (LOC), and each of these forms of carbon need to be taken into account when using carbon isotopes for paleoenvironmental studies in wetlands (Lu et al., 2014). Previous research shows that when conducting isotopic analysis on soils it is useful to compare the total soil organic carbon to the residual, long-lived residue of organic carbon known as the humin fraction. This is a useful method when determining past vegetative communities both natural and agricultural (Webb et al., 2007). I used the method of Webb (2007), which involves removing carbonates and extracting humic acid and fulvic acids, and then using an isotope ratio mass spectrometer (IRMS) to analyze the residual soil humin fraction. Comparison of the δ13C ratios of total organic carbon and of the humin fraction of sediment organic matter provides a more accurate model of organic matter degradation and fractionation throughout these systems over time (Meyers 1994).

In this analysis I use the Thermo Electron MAT 253 Isotope Ratio Mass Spectrometer (IRMS). Samples are placed in small foil cups and then dropped into the sample introduction system where CO2 is formed. The produced CO2 is analyzed for masses 44, 45, and 46 . ^{13}C and compositions within each sample are conveyed as changes in per mil (‰) of the ratios $^{13}C/^{12}C$ in the sample against an international standard, usually against Vienna PeeDee Belemnite (VPDB) for carbon isotopes. The equation that I use is standard amongst most isotope scientists. Here I site Anderson (2008), but a similar equation can be found throughout the literature and is:

$$\delta = \left[\left(\frac{\text{Rsample}}{\text{Rstandard}}\right) - 1\right] * 1000$$

where Rsample and Rstandard are the ratios for $^{13}C/^{12}C$ or the ratios for $^{15}N/^{14}N$ of the sample and international standard, respectively. The JSG Stable Isotopes lab uses internationally distributed standards such as VPDB and other regional standards for calibration purposes, as well as an internal standard, UTM, that is used to monitor and address time drift. The software I use with this IRMS system is called ISODAT.

2.4.5. Paleoecology and Microcharcoal

Microscopic charcoal has been used in various parts of the Maya Lowlands and in other regions as a proxy for estimating the frequency of fires at a variety of scales. Charcoal can be transported in many ways during fire events, both anthropogenic and natural, including through fluvial systems, but also through wind via the smoke column. By quantifying microscopic charcoal within soil horizons within wetlands, we can determine where peaks of charcoal occur within the sedimentation record and tie these peaks back to fire frequency and magnitude. Within the Maya Lowlands, studies of pollen, erosional episodes, and charcoal have been linked to deforestation and widespread clearing, especially during the Maya Preclassic time period. This proxy can assist within my case study sites to determine time periods of increased fire events throughout the wetland system.

In order to extract charcoal from wetland soils, I used a revised method based on Turner (2007) and Anderson and Wahl (2014). First, I subsampled 2g of wet sediment from discrete soil horizons from cores and pits. This sediment is disaggregated in beakers with 80ml of deionized (DI) water and 20 ml of 10% hexametaphosphate. After disaggregation, clays arepippetted out of the beakers and the samples are rinsed several times. Samples are then wet sieved through a 180 μm sieve and the water is pipetted out. Next, I added 10% HCL to remove all carbonates, and following this, I spiked each sample with two tablets of exotic Lycopodium spores from Lund University (batch 3862, 9,666 spores per tablet), which serve as a reference and standard for the analysis. After another wash, I washed the samples from the beakers using 15ml of Sodium Polytungstate (SPT) calibrated to a specific gravity of 2.5 g/ml. This heavy liquid seperates the microcharocal from any remaining clays and detritius. Following this, the samples are centrifuged for 10 minutes at 1000 rpm. I then pipette off the top pellet of SPT which contains the microcharcoal, back into beakers, which is then washed twice with DI water. After removing excess water and recovering the SPT for cleaning and reuse, samples are transferred into 2.5 ml storage tubes and mounted onto slides with glycerol jelly and sealed with entellen.

I use Turner's (2007) method to count and identify charcoal particles on the slides against the Lycopodium spike. Following the standard of previous scholars working in the region, I counted charcoal particles between 30μm and 90μm, and then greater than

90µ. Fragments under 10 µm are not counted. The criteria for determining the presence of charcoal is as follows: Particles should be completely opaque and black,sometimes with a blueish hue. The shape is generally angular-sub angular, and may contain a cellular structure.Following the method of Innes et al., (2004), I calculated the quantitiy of microcharcoal in each sample in which a particle of about 30 µm is the basic measurement and the following calculation is used:

Charcoal concentration (whole sample) =
(exotic spore added × charcoal counted)/exotic spore counted

Charcoal concentration per 1 gm =
(1/sample weight) × charcoal concentration(whole sample)

Chapter 3: Remote Sensing of Maya Agroecosystems[1]

Increasingly, archaeological evidence suggests that Classic Maya (AD 250-950) intensively manipulated, sustained, degraded, and revivified their environment at different times and different scales through a variety of soil and water management strategies (Anselmetti et al., 2007, Scarborough et al., 2012; Beach et al., 2015a). Today the lowlands of Belize, México, and Guatemala are again being intensively utilized for crop cultivation by modern farmers. The Maya Lowlands therefore has a long history of human manipulation and farming within its wetlands, and in order to better understand the systems as they are today, we must quantify and understand the deep history of human impact within this system. To answer these kinds of big impact questions, geoarchaeological researchers in the Maya Lowlands engage in quantifying and assessing ancient Maya land use and, develop models for natural and anthropogenically influenced hydrologic patterns and identify anthropogenically induced vegetation change over time (Dunning et al., 2000, Guderjan 2007; Wahl et al., 2014; Beach et al., 2015, 2017). Remote sensing technology intersects elegantly with these environmental questions as it provides a multi-component spatial platform in which to visualize and quantify the remnants of ancient land use strategies.

In the Maya Lowlands, pedestrian survey can be difficult, costly, and at times, slightly treacherous. Low-lying wetland areas, sinks, and bajos, even during the dry

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[1] Parts of Chapter 3 appear in the previously published work: Sixty Years of Remote Sensing in the Maya Lowlands: A Review of Techniques and Tools by Samantha M. Krause, Thomas Guderjan, Timothy Beach, Sheryl Luzzadder-Beach (2016) in *Changes in Latitudes, Changes in Attitudes: Transitions and Thresholds throughout Central America and Beyond*, (p.61-80) published by the Center for Archaeological and Tropical Studies Occasional Papers, University of Texas, Austin. I served as primary author and analyst, coauthors provided support in the form of grants and permits.

season, are often overgrown and it is difficult to make sense of agricultural microfeatures from the ground. The study of such anthropogenic wetland landscapes therefore must involve a variety of multidisciplinary techniques to better pinpoint and excavate possible features. This chapter explores how remote sensing has assisted and complimented geoarchaeological efforts within the Maya Lowlands and reviews the remote sensing tools that archaeologists have used to better visualize, map, and understand wide-scale Maya agriculture and provides evidence of remote sensing success within my own case study areas as I quantify prehistoric agricultural fields at an unprecedented scale. Wetlands in the Yucatán Peninsula are, are previously discussed in Chapter 2, poorly mapped in general. Here I explore a variety of datasets, including Google Earth, Multispectral imagery (Geoeye) and LiDAR imagery to better visualize and quantify anthropogenic features (canals and raised fields) in riparian wetlands that are not accounted for within the Global Lakes and Wetlands Database (GLWD).

3.1. ARCHAEOLOGY AND MAPPING IN THE MAYA LOWLANDS

Over the past thirty plus years, researchers in the Maya Lowlands have introduced a variety of technologies to their study sites, including new dating methods, site prospecting equipment, and technological aids to map making, such as GPS units, drones, and aerial survey. Comprehensive mapping not just of site centers but also of hinterland and agricultural regions has become more prevalent as these technologies have become more available to researchers and the public. In the past ten years, we have seen a dramatic spike in remote sensing technologies being applied to previously inaccessible areas, and this has allowed researchers to consider larger scale questions concerning the scale and scope of large agricultural systems, macro-economics, and environmental adaptation in this region, particularly during transformative periods, such as the

Preclassic to Classic transition and the Classic to Postclassic transition. Comprehensive mapping and the subsequent necessary field verification has provided a wealth of information especially on agricultural features such as terraces, reservoirs, wetland canals and raised agricultural fields.

Prior to the late 1960s, most archaeologists in the Maya Lowlands subscribed to the idea that ancient populations in this region subsisted completely on small agroforestry efforts, household gardens, and swidden agriculture methods (Seimans 1972). While all of these methods of agriculture have been documented at various sites throughout the ancient Maya world, by the late 1960s and into the 1970s, archaeologists began to consider that the higher population densities, especially within the Maya Lowlands, must have demanded a more intensified agricultural system of terraces and raised field systems that spanned many hectares across various environments; bajos, inundated wetlands, broad savannas, and upland forests alike (Turner 1974). First, intensive aerial surveys and then both passive and remote sensing demonstrated the vast Maya imprint on the environment within this region. Canal and field systems appear in aerial surveys and in remotely sensed imagery as a rectilinear, squared off, or otherwise unnatural pattern on the landscape (Figure 3.1). These systems, used to direct water through seasonally inundated landscapes and to build arable land above the water table, occur within riparian floodplains, in and around bajos, and at the bases of escarpments.

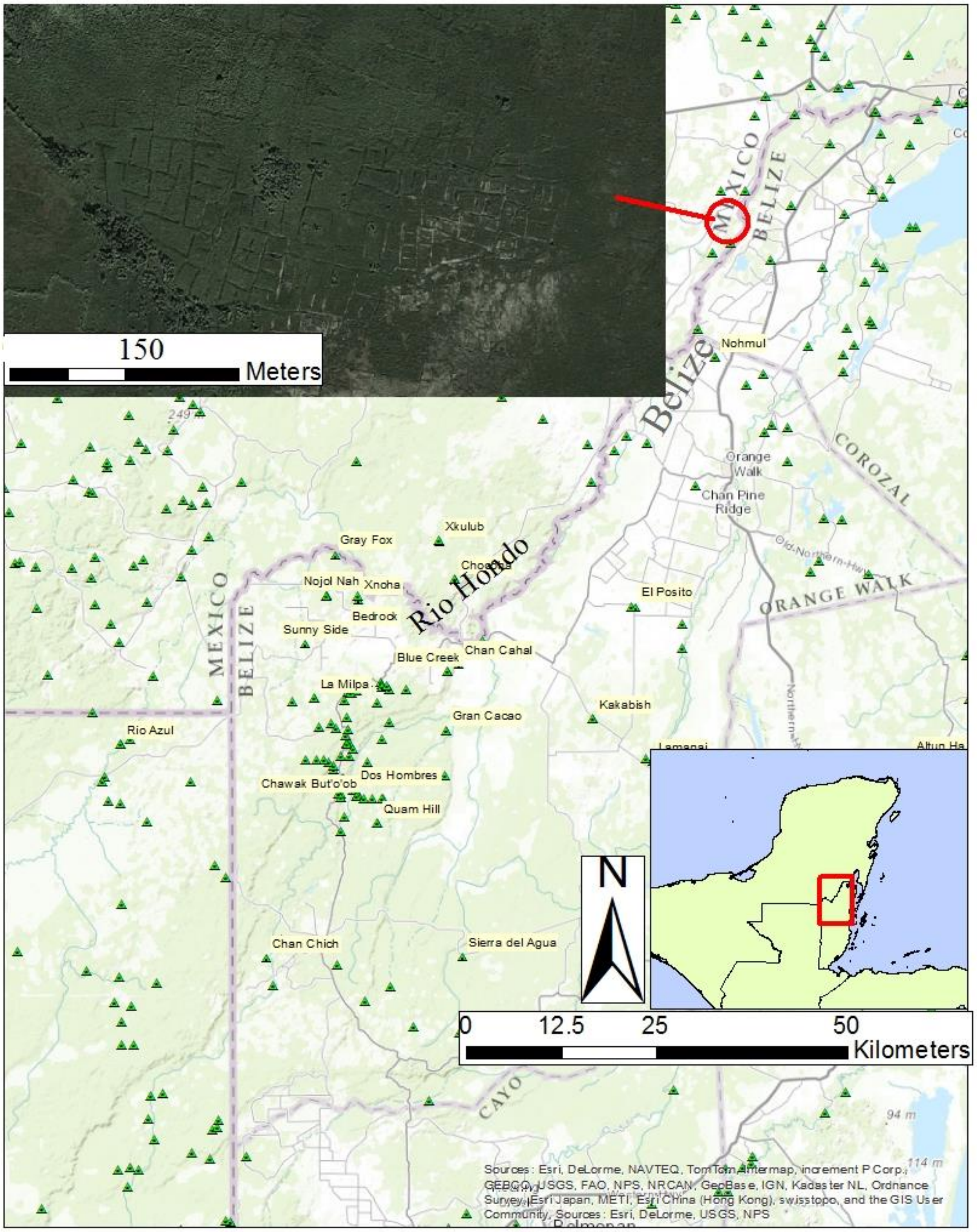

Figure 3.1: General Location Map and Example of Maya Field Systems along the Rio Hondo

Researchers working along the Rio Candelaria in Campeche, México, were some of the first to notice and consider patterned features that were interpreted as extensive field and canal systems near the Maya site of El Tigre (Siemens 1972). Siemens and his coauthor Puleston at that time drew heavily on the prehistoric and history agricultural features that had been documented in other sites across other regions in the Americas, such as the *chinampas* of México (Coe 1964, Doolittle 1990) and the early work on *camellones* (ridged field systems) of Ecuador, Bolivia and Peru (Denevan 1970). Shortly after Siemens and Puleston began to document the Rio Candelaria field systems, B. L. Turner published his own finding regarding ancient Maya agriculture. Turner (1976, 1981) documented a series of large scale terraces over a 10,000 square kilometer area along the Rio Bec, which runs through the Mexican states of Campeche and Quintana Roo. These early Rio Bec field systems have continued to play a part in better understanding the social dimensions of "micro-regions" and "nuclear zones" of habitation during the Maya Classic period (Lemonnier, 2013; Nondédéo 2013). Only a few years after these initial systems were identified along the Rio Candelaria and Rio Bec, strikingly similar features were discovered along the Belize-México border on the Hondo river (Jacob 1995). Siemens estimated in 1983 that there were at least 3,200 hectares of anthropogenically modified field systems within these Belizean wetland systems. Robust debate ensued over the next several over exactly what the extent of these features could be quantified to, specifically in the case of "how anthropogenic" these features actually were throughout wetland systems (Jacob 1995). Currently, more emphasis is being placed on quantification, excavation, and new technological efforts of these features to determine how they tie into the urban setting, timeline, and subsistence of the ancient Maya (Guderjan 2011, Harrison-Buck 2013, Harrison-Buck 2015).

Perhaps these early debates concerning the validity of these were warranted, as early remote sensing and soil geomorphology techniques needed to catch up with the research question at hand. Early efforts to quantify the extent of ancient agricultural systems using oblique angle photography and SEASAT synthetic aperture radar (Adams 1981) in the southern Maya Lowlands were largely criticized Pope and Dahlin in 1989 due to problematic radar data. These early data sets certainly provoked more scrutiny into the authenticity of these cultural features. Critics denounced this original aerial survey because of the claim that it grossly exaggerated the amount of anthropogenic modification on the landscape (Pope and Dahlin, 1989; Adams et al., 1990), resulting in many years of criticism and spirited debate over the importance of Maya wetland agriculture (Bloom et al., 1985; Fedick and Ford 1990, Adams et al., 1990, Baker 2003; Luzzadder-Beach et al., 2012).

These early efforts were an attempt for archaeologists to transition to a more holistic understanding of the Maya landscape through the use of a new vantage point and recognize the plethora of remotely sensed data that has been procured by a variety of researchers following these first efforts. These primary endeavors marked the first time within Mesoamerican archaeology that remote sensing efforts were considered as a valuable resource in which to employ a scale driven analysis of agricultural patterns throughout the Maya Lowlands. In the 1990s, excavations of Maya sites and associated agricultural feature intensified along the Rio Hondo. Similar research projects were conducted by Pohl and Pope around Albion Island, a Maya site next to the Rio Hondo (Pohl 1990, Fedick 1996). In the early 2000s, Pyburn focused excavations on water control features at the site of Chau Hiix in the Crooked Tree wetlands along the New River (Pybyun 2003). Meanwhile, Guderjan and his collaborators recognized canal systems at the site of Blue Creek (Beach 2009, Beach 2011) and began an extensive campaign to better understand the paleoecological significance of these features. In the mid-late 2000s, Steven Bozarth's work on ancient agricultural systems around the Blue Creek area yielded pollen evidence for a variety of different cultigens, including maize (*Zea mays*), sweet potato, breadnut, cacao, avocado, wild banana, and various other types of agricultural plants (Beach et al., 2009). Based on these intensive excavations around the Three Rivers Region, scholars have developed several complex and finely resolved models of human-wetland interaction and Maya occupation and resilience over different time periods. These kinds of multi-proxy projects highlight how wetland patterned field research has shifted over the years. Maya archaeologists have moved from the question of whether or not these systems are anthropogenically modified to different questions. Today, the focus of research has turned to wetland development, preoccupation through abandonment, cultivation strategies, and shifting environments in the face of large scale regional drought patterns (Luzzadder-Beach et al., 2012, Harrison-Buck 2014, Dunning et al., 2015). Remote sensing efforts are an important component to this research, first as a field checking and quantification technique, but also as way to understand patterns of land use and development across a cultural region. In this research I use a variety of sensors to capture the maximum amount of modification possible (Figure 3.2)

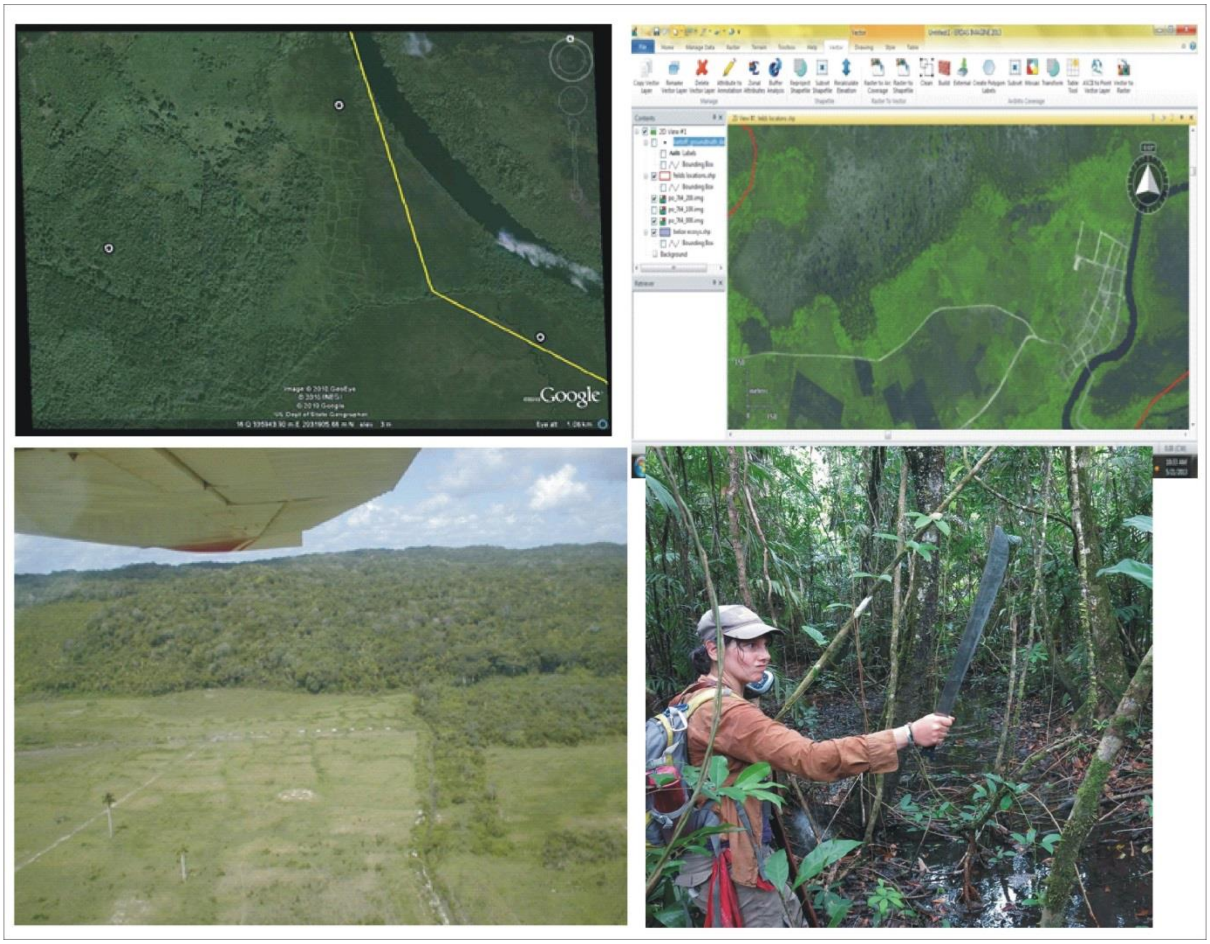

Figure 3.2: A variety of media depicting ancient Maya agricultural modifications. Top: Google Earth, Middle: Erdas IMAGINE remote sensing software, Bottom left: Aerial survey, Bottom right: Pedestrian survey with Ashtech GPS unit (canal in background).

3.2 Natural and Environmental Considerations

Understanding the natural geomorphology of the Maya Lowlands is an important component to mapping and remote sensing efforts. Within wetland environments, several distinct natural patterns emerge due to pedoturbative processes. Wetlands, especially tropical wetland areas within the Maya Lowlands, are situated on a bedrock primarily composed of back-reef, lagoonal limestone (Beach et al., 2015). This karst-dominated environment has a ground water table that is very near to the surface, promoting the development of wetland soils, primarily histosols and veritsols (Beach et al., 2015). Wetland morphology processes in this area include, but are not limited to the following formation development: gilgai patterned relief (Figure 3.3.), tree islands, and ridge and slough feedback systems. Each of these wetland features has been studied and considered by tropical system archaeologists, soil geomorphologists, and wetland biologists alike in the tropical Americas and beyond (Turner et al., 1981; Watts et al., 2014), yet there is still much the be gleaned regarding soils formation, environmental feedback loops, biologic modification (including anthropogenic factors), and the formations that arise from the combinations of all of these processes. Current remote sensing efforts consider visualization techniques that can assist in determining which environments are likely to be anthropogenically modified, which are exhibiting these patterns of natural wetland morphology, and which are likely to be a combination of ancient human modification and natural processes. Remote sensing of these areas helps to inform geoarchaeologists currently working within the Maya Lowlands as the most fruitful areas in which to focus pedestrian survey efforts as well as excavation.

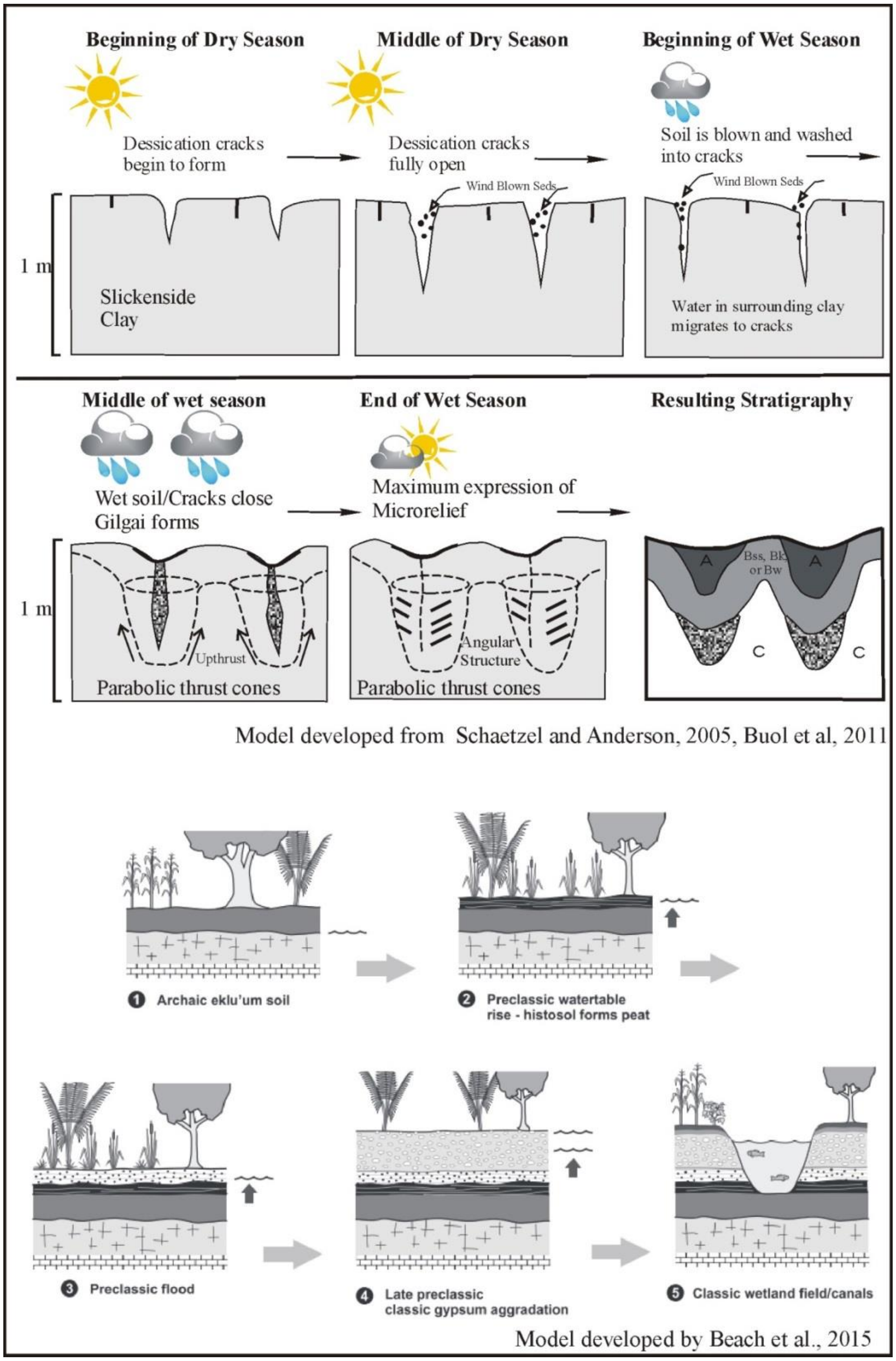

Figure 3.3. A comparison of natural gilgai formation and ancient canal and field building.

3.3. Data Acquisition and Methods 2010-2011:

Together with T. Guderjan, I document this most recent phase of wetland pattern quantification along the Rio Hondo as beginning with a series of flights in a small aircraft from the modern Mennonite village of Blue Creek to just southwest of Corozal Bay, the Belizean town that borders the Mexican town of Chetumal, Quintana Roo (Guderjan & Krause 2011). The 2010 flights were reconnaissance missions primarily, our main goal was to determine whether we could visually identify and document ditched field systems using GIS technologies and begin building a database of oblique aerial photographs and ground truth data for field patterns along this river system. Time stamps on the photographs along with a hundreds of track logs taken with a Garmin Oregon 550 series. Each set of photographs and track log from the GPS was organized within a database using ESRI's ArcGIS 9.3 and the ArcPhoto tool script. This extension called ESRI's ArcPhoto Tools is a set of geoprocessing tools that enhances the ArcMap user interface. The extension allows the user to quickly import a large set of digital photographs into the framework of the map. These photos are tied to georeferenced points and are quickly displayed on the map as a set of "map tips", thumbnail images that can serve as annotations or visual reminders for the vector point features (Figure 3.4). This is a rapid method for transforming usually bulky data sets such as large photo sets into spatial features.

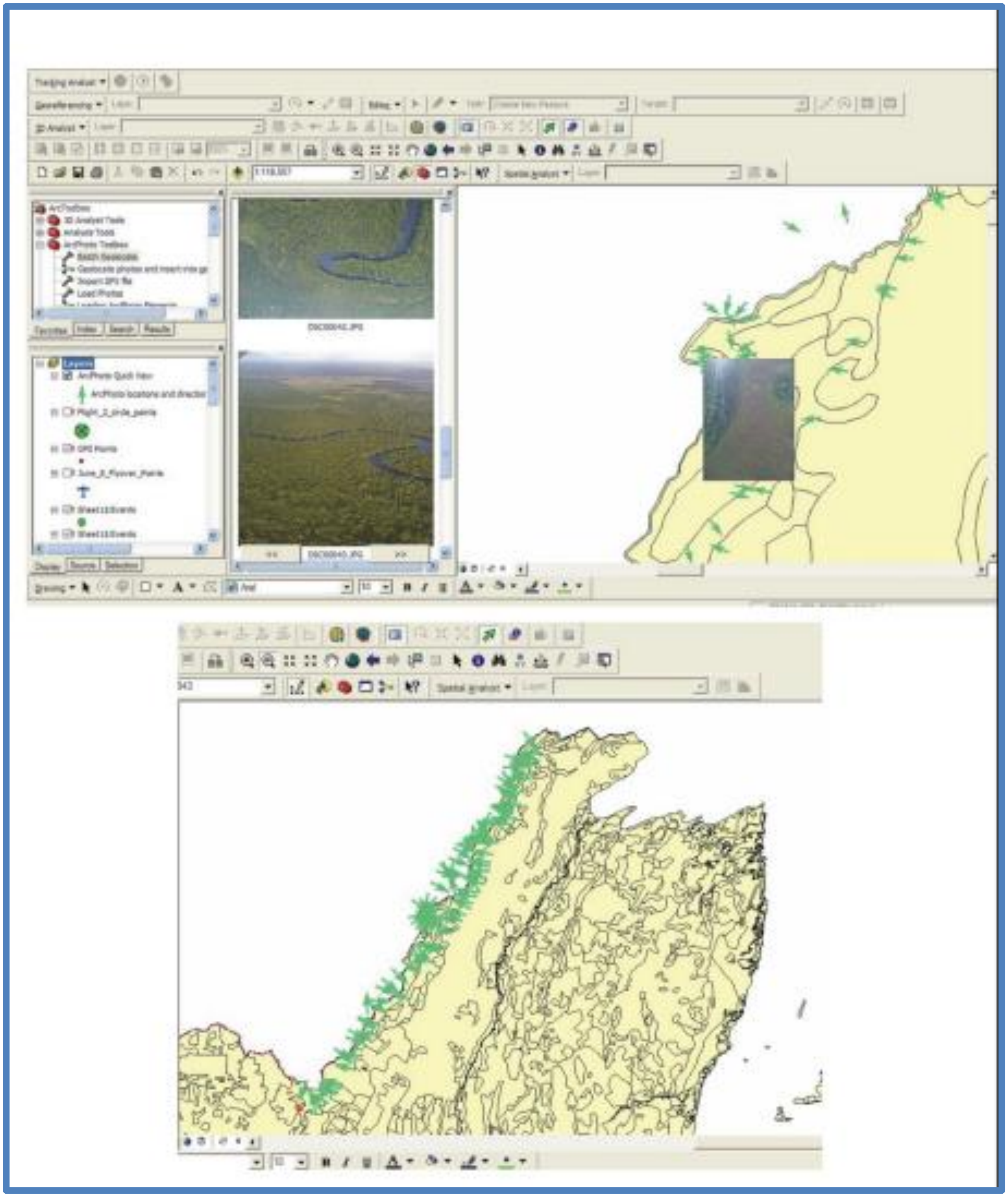

Figure 3.4: Examples of data management during 2010-2011 field efforts.

Along with the hundreds of track record points and just as many georeferenced photos taken from these initial flight series, we collected a series of ground truth points on landmarks along the flight path to insure spatial data quality for the entire database. Ground truth points were mostly collected along cross roads, and on buildings in towns along the river that were easily distinguishable from the air.

3.4. Data Acquisition and Methods 2012-2013:

These original explorative surveys yielded intriguing results detailed by Guderjan in 2011. In summary, we were able to document at least fourteen sets of ditched fields in the Río Hondo floodplain, several of which have certainly been studied in previous work, especially those around Albion Island. The preliminary results of the 2010-2011 field seasons encouraged the research team to continue efforts in visualization and remote sensing throughout this area. The research team hypothesized that the presence of these canal features could be revealing only a small part of a much larger ancient agricultural system, due to natural wetland deposition and infilling, along with a combination of reforestation in some areas, and intensive modern plowing and urbanization in other areas along the river. In 2012, Colleen Hanratty and Thomas Guderjan of the Maya Research Program (MRP) pursued a research grant to procure Geoeye multispectral imagery for the length of the Rio Hondo that was identified in the 2010-2011 surveys (Figure 3.5). This image set was obtained with a grant through the Geoeye/DigitalGlobe. MRP acquired a set of satellite images that were obtained from the IKONOS satellite in the winter of 2013. This satellite is multispectral, and utilizes five bands, the panchromatic band, the red, green, blue bands, and the near infrared bands, orbiting the earth at 681 km, with a three day revisit time (Parcak 2009). The resolution for the IKONOS sensor is 0.8 m for color imagery and 3.2 m for the near infrared band. Although this satellite uses less bands than Landsat, a great deal of information can be gleaned from various processing techniques and pattern recognition algorithms detailed in the previous sections of this report.

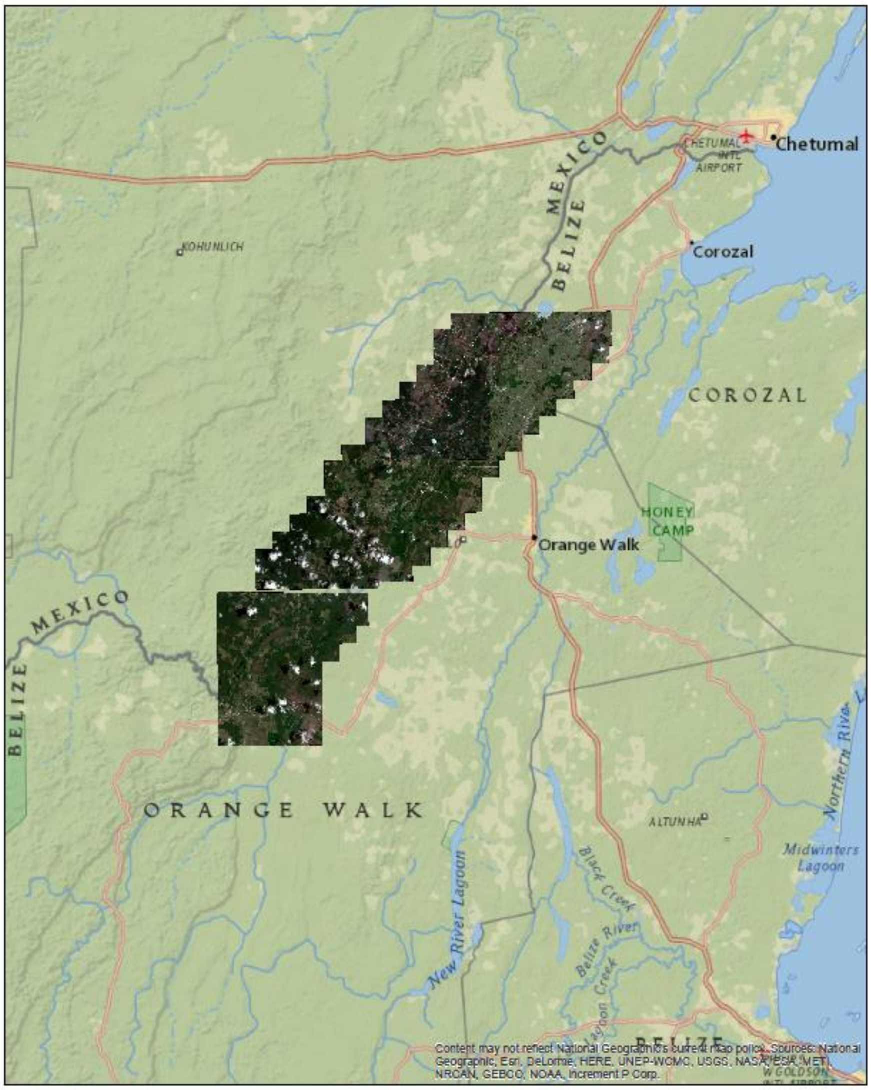

Figure 3.5: Swath of Geoeye multispectral imagery along the Rio Hondo

I preformed all image transformations and visualization techniques with ERDAS Imagine 9 software. Transformed images were then transferred over the MRP GIS geodatabase, run through ESRI's ArcGIS 9.3-10 software package. In ERDAS, the Geoeye multispectral imagery of the project area was first layer stacked in the RGB color bands.Ie then used the mosaic tool to combine the georeferenced and layer stacked images for easy visualization of the entire swath of data for the Rio Hondo. I created several copies of this RGB mosaic image of the data swath was to perform a variety of statistical analyses on the imagery. Using the IMAGINE software, I applied a variety of edge detection filters on the imagery to determine the best filters to use when attempting to locate new canal features. The software uses Gaussian smoothing kernels to process these different edge detection filters. A default kernel library containing some of the most common convolution filters is supplied with IMAGINE, and so I was able to explore a variety of techniques, including 3x3 Edge Detect, 3x3 Edge Enhance, 3x3 Haze Reduction, and more. These techniques were used after Lasaponara and Masini in 2006, and a qualitative visual comparison of the imagery after edge detection filters yielded a quicker visualization of patterned landscapes along the Rio Hondo. This simple technique, however, cannot be used to determine whether or not the emerging patterns are natural or anthropogenic.

I used ERDAS to apply an NDVI (normalized difference vegetation index) analysis to the imagery (Figure 3.5a and 3.6b). Traditionally, NDVI has been used primarily by biologists and ecologists with the primary goal of monitoring vegetation health and vigor (Lasaponara 2006, Schowengerdt 2007). NDVI is a quantitative measure of biomass vigor. This function acquires spectral reflectance measurement operates through an ERDAS model that utilizes the following equation:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{VIS})}{(\mathrm{NIR} + \mathrm{VIS})}$$

In which the red color band (VIS) is indicative of chlorophyll pigment absorption and the near infrared band (NIR) is indicative of the high reflectance of leaf mesophyll (Schowengerdt 2007). This index has recently become popular with archaeological remote sensing efforts especially when determining the location of structures archaeological sites due to vegetation change (Parcak 2009). In this case, canal features will show up darker and less vegetated in an NDVI image, and surrounding tropical vegetation will be illustrated in light gray/white color schemes.

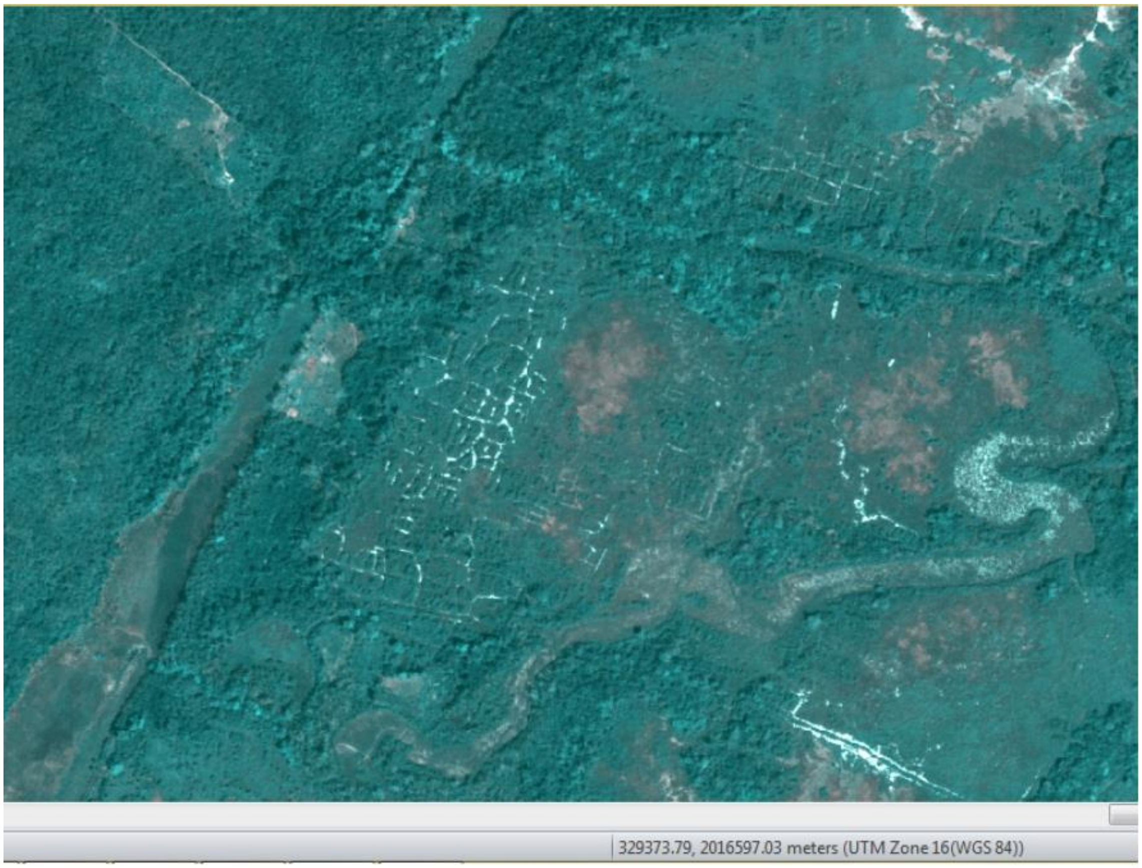

Figure 3.6a: True Color Imagery of both ditched field and natural floodplain features along the Rio Hondo

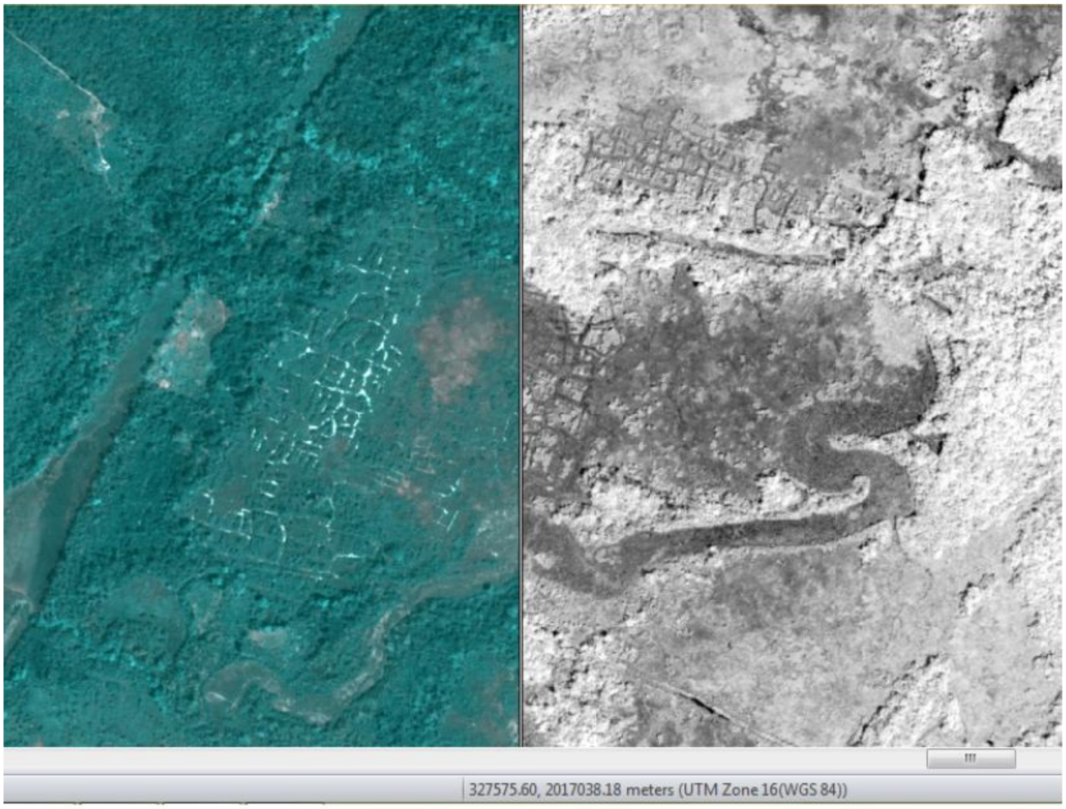

Figure 3.6b. The same image as above with NDVI applied to half of the screen.

The next visualization technique I applied to the Rio Hondo dataset mosaic was a Tasseled Cap Transformation, originally after Kauth in 1976, but now used in many remote sensing processing analyses (Figure 3.7). Tasseled Cap is useful tool can be used with multi or hyperspectral imagery. The technique compresses spectral data into just a few signatures that are output into ERDAS, ENVI, or ArcGIS as three different bands (Kauth 1976, Schowengerdt 2007). The first tasseled-cap band corresponds to the overall brightness of the image. The second tasseled-cap band corresponds to "greenness" and is typically used after a similar fashion as NDVI. The third tasseled-cap band is often interpreted as an index of "wetness" of the soil or as surface moisture in general. These first three bands contain the primary amount of information within the analysis, and any other bands that are created are simply considered to be “noise” bands (Schowengerdt 2007).

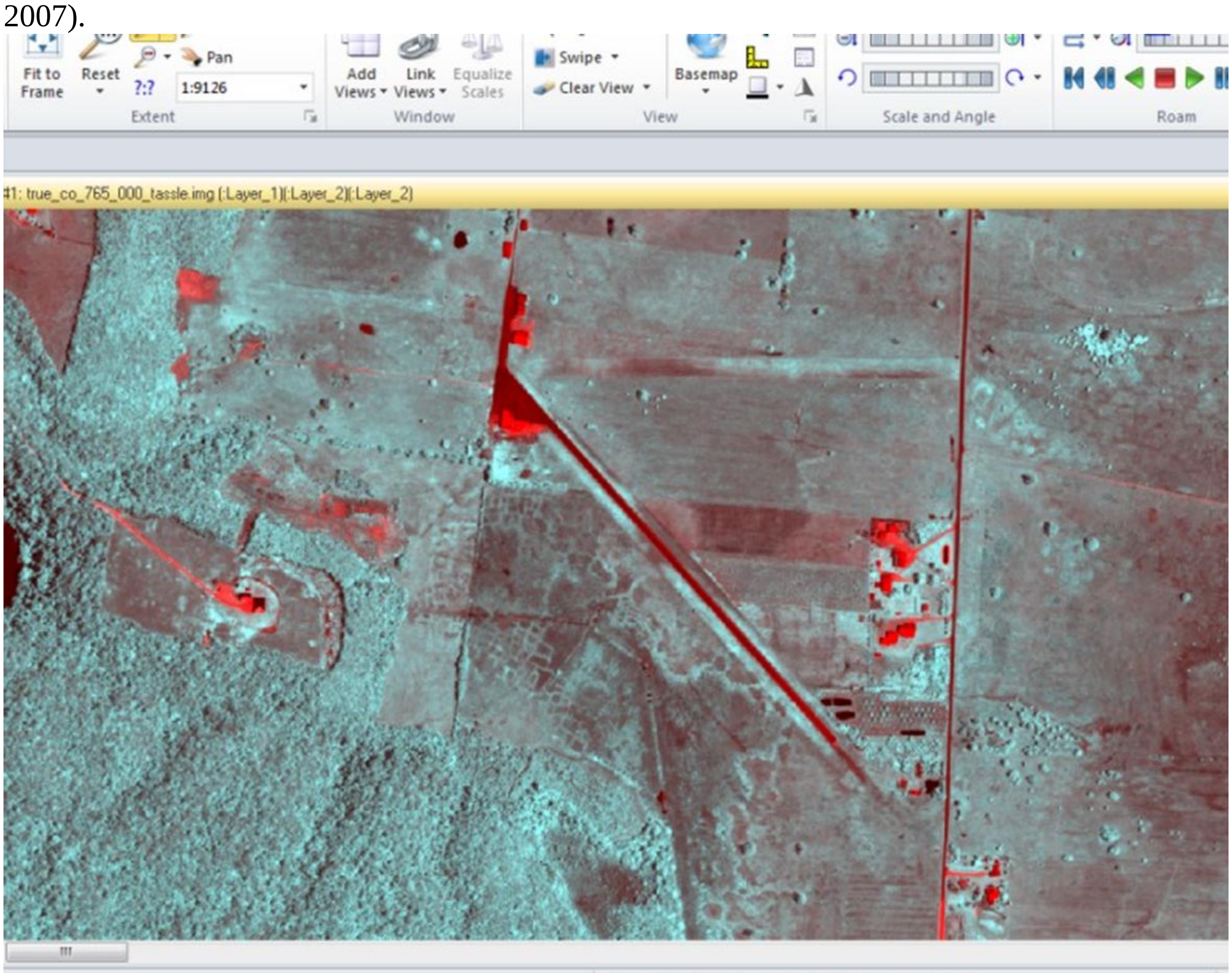

Figure 3.7. Well studied ancient Maya canal systems south of the Rio Hondo, adjacent to modern agricultural fields and an airstrip.

I also applied a Principle Component Analysis (PCA), to the Rio Hondo multispectral mosaic, which is simply a classification analysis that reduces the amount of redundant pixels in the spectrum. Running a PCA model on the Rio Hondo dataset creates inter-band correlations and helps to obscure extraneous data, compressing the bands into the principle variables. In the case of Landsat imagery, the imagery will be reduced to seven principle components. In the case of this Geoeye imagery, the dataset is reduced to five principle components. This is incredibly helpful when working with a tropical riparian dataset, such as the Rio Hondo, because the various types of flora are reduced down to simply "vegetation", that is represented in one color, all urban features are reduced and represented as one color, and, most importantly, all water features are reduced down to one component. This particular PCA is fairly simple, but, as suggested by Parcak in 2009, with more robust data sets it might be possible to run another PCA using hyperspectral imagery and NASA's library of reflectance data. In doing so, it could be possible to use PCA to pinpoint soils with elevated phosphorus levels, a trait that archaeological activity areas have. Searching for soil phosphorus with PCA could allow us to better determine the extent of activity and processing areas around ancient Maya canal systems, which could in turn lead to a more robust analysis of population density and overall possible crop yields during times of use. This kind of analysis is still theoretical, but could be possible by combining our Geoeye imagery with hyperspectral imagery such as ASTER or AVRIS.

After processing the Geoeye imagery using the techniques discussed above, I used ESRI's ArcGIS 9.3 and 10 to create vector data sets pinpointing the locations of ditched field locations. Polygons were traced around areas that were considered to be "probable" after looking at the imagery under these filters (NDVI, PCA). More defined anthropogenic canal and ditch features that were considered to be highly likely were traced as line files. These files were then merged with canals that had already been mapped using aerial imagery and years of pedestrian survey (Figure 3.8).

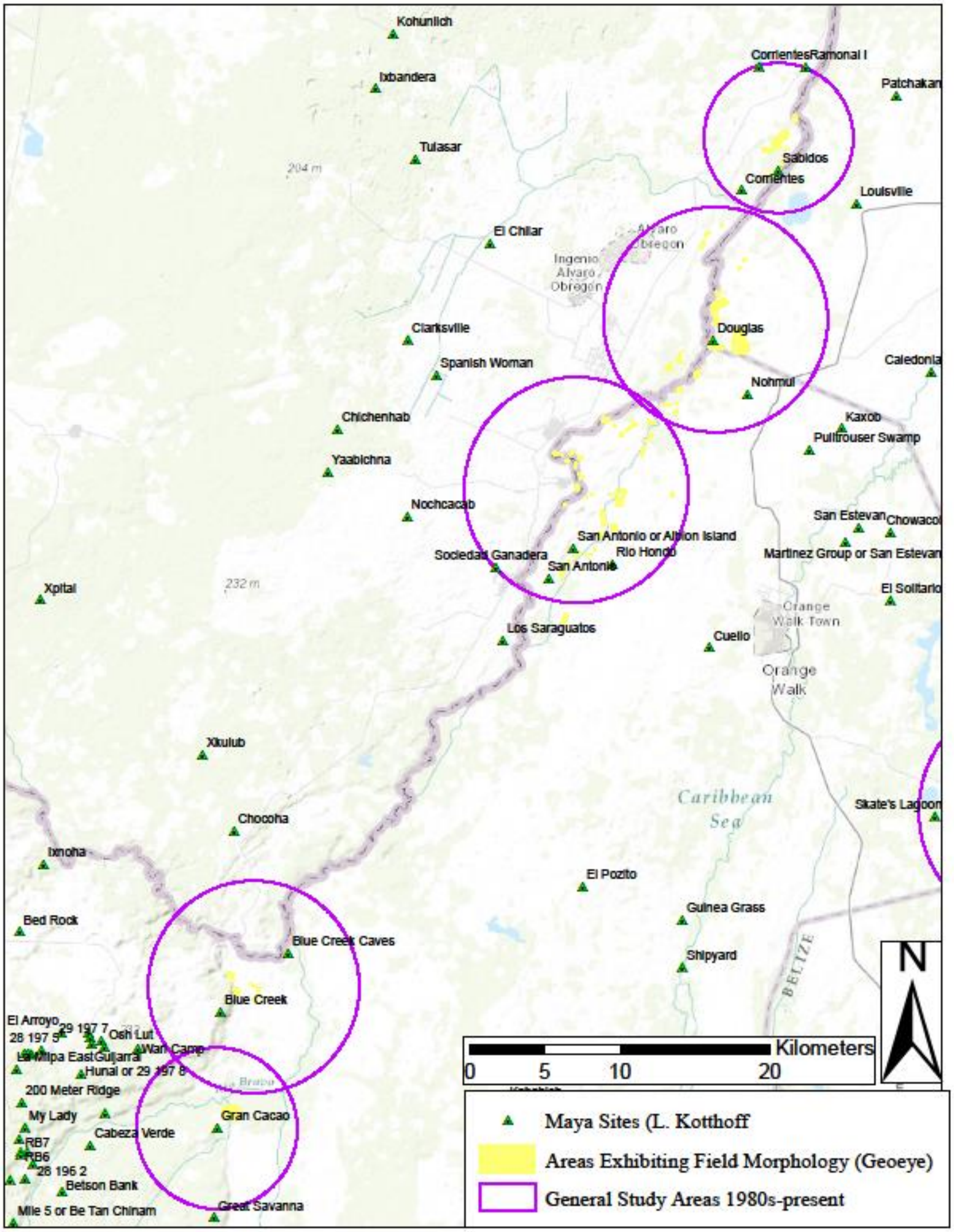

Figure 3.8. Locations along Rio Hondo exhibiting ditched field morphology.

3.5. Data Acquisition and Methods 2016-2017:

Increasingly, archaeological projects have turned to LiDAR technology to accurately map sites, especially sites that are difficult to access. LiDAR data collection can be terrestrial or it can be collected via an aircraft survey. Many archaeological projects throughout Latin America have utilized LiDAR with great success over the past ten years, most notably at the site of Caracol in Belize and Michoacán, México (Chase et al., 2012). LiDAR produces what is known as point cloud data, which is collected via a pulsing or continuous laiser and provides measurements on the laser's returns. Each LiDAR system works off of a basic equation that can again be manipulated or added to depending on the project and function:

$$t=2(x/c)$$

In which c is the speed of light, the delay between transmitted and backscattered pulses from an object is t and the distance is x (Fujii & Fukuchi).

The point cloud is processed to create DEMs (digital elevation models) of the earth surface as well as a DSM (digital surface model) which provides information on canopy height. In general, for archaeological and geomorphic purposes, the DEM is more commonly used to understand settlement zone patterns and human impacts on the landscape. Architecture as well as micro-relief patterns such as ditched fields, raised canals, and terraced ridges can all be detected using LiDAR-derived DEMs.

In the summer of 2016, the Northwestern Belize Research Consortium acquired a swath of LiDAR data that included much of the Program for Belize Archaeological Project (PFBAP) study area and surrounding farmland as well as a portion of the Belize side of the Rio Hondo floodplain. This LiDAR dataset was collected by the National Center for Airborne Laser Mapping (NCALM) which is operated jointly by the

Department of Civil & Environmental Engineering at the University of Houston, and the Department of Earth & Planetary Science at the University of California, Berkeley. The flying height for the aircraft was 600 AG with a swath width: 400 – 500 m. The overlap between adjacent swaths was 50% and the scan angle was ± 15 – 25 degrees. The height accuracy (on open & hard flat surface) was 4 - 8 cm (one sigma) and the horizontal accuracy: 15 - 20 cm (one sigma). The number of points per square meter was 20. This LiDAR dataset provided the various research groups working in Northwestern Belize with a window by which detailed settlement zone patterns could be assessed, including the presence of even more wetland agricultural systems than had been previously known, especially within the Birds of Paradise wetland (previously discussed in Beach et al., 2008 and Luzzadder-Beach et al., 2012). I used this LiDAR data set as another form of remote sensing that allowed us to detect Maya agricultural systems in new areas with great success.

In this region, the strength of LiDAR lies within its ability to digitally remove the canopy returns within the point cloud, leaving behind the bare earth DEM. Therefore, LiDAR works the best in this region under high canopy systems with more openings by which the laser pulses are able to hit the physical ground surface. In contrast, areas with low, grassy vegetation were too close and dense to the ground surface, which caused too much noise at ground level, rendering canals invisible with this technology. Therefore, I determined that canals that were quite visible in grasslands through multispectral imagery (due to coloration differences between grasses in the micro relief or the presence of standing water), were practically invisible with the LiDAR scan. Canals hidden beneath tall canopy, on the other hand, were easily discernable with the LiDAR DEM (Figure 3.9 and Figure 3.10)

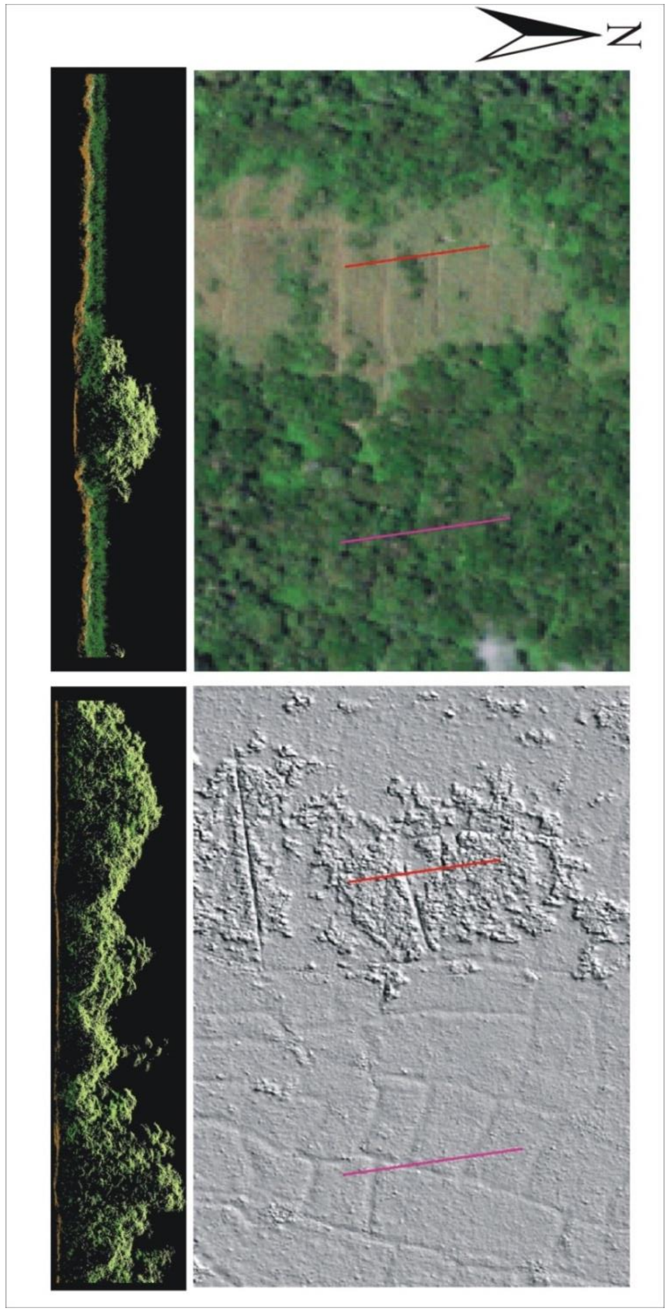

Figure 3.9. Point cloud profiles of transects running through a savanna and a high tropical forest. Each transect is about 100 m. Note the differences in canal visibilities.

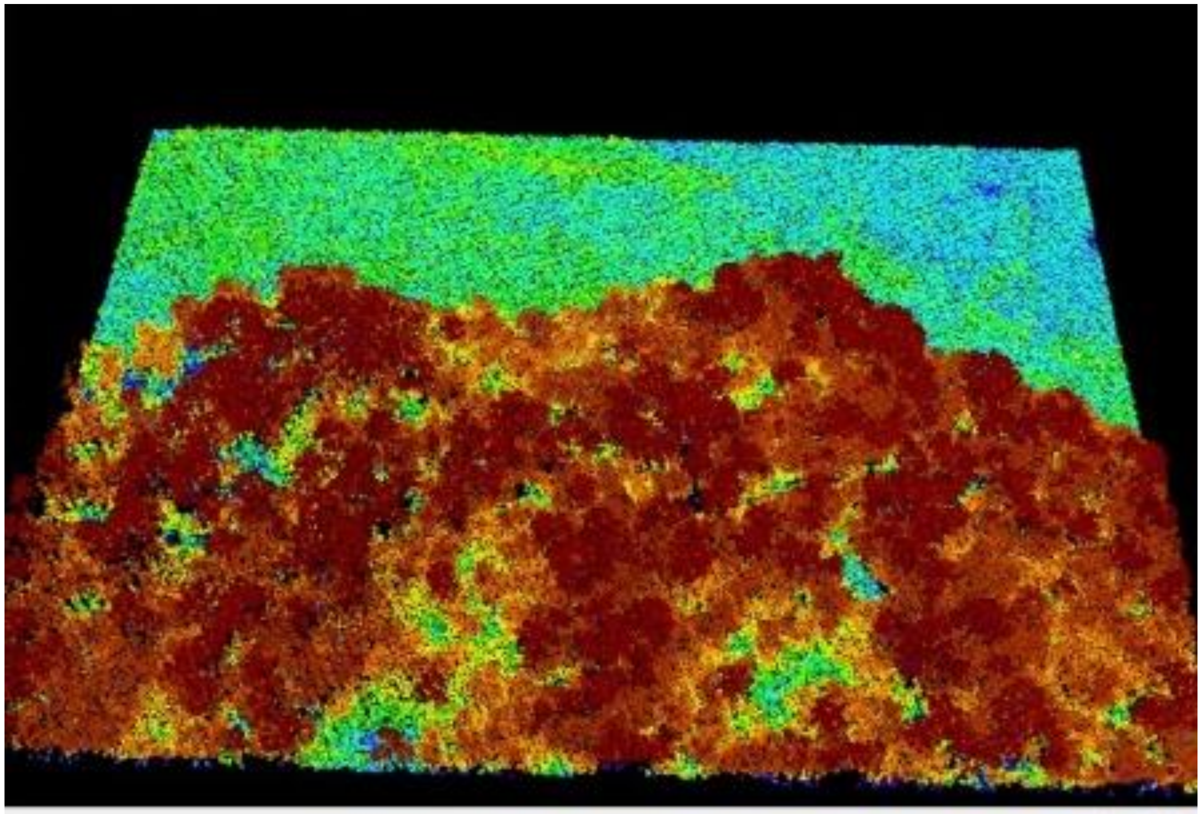

Figure 3.10. A screenshot of two distinctly different canopies (savanna to the north, tropical forest to the south) viewed in 3-D via the LiDAR point cloud. Red indicates higher point cloud returns and green/blue is lower.

As with the multispectral imagery previously, I used a few different techniques in order to enhance what I was able to visualize with the LiDAR. The main technique used to enhance the LiDAR imagery was the SkyView Factor Relief Visualization Toolbox (RVT) courtesy of the Institute of Anthropological and Spatial Studies of the Slovenian Academy of Arts and Sciences (Kokalj et al., 2011; Zakšek et al., 2011). With the RVT toolbox, I created a simple local relief model of the new region of wetland agricultural located within the Birds of Paradise wetland system, previously thought to be only about

100 acres total. The simple local relief model (SLRM) helps in this case to enhance these low lying areas and assists in visualization of even the more sedimented and shallow canals (Figure 3.11 and Figure 3.12).

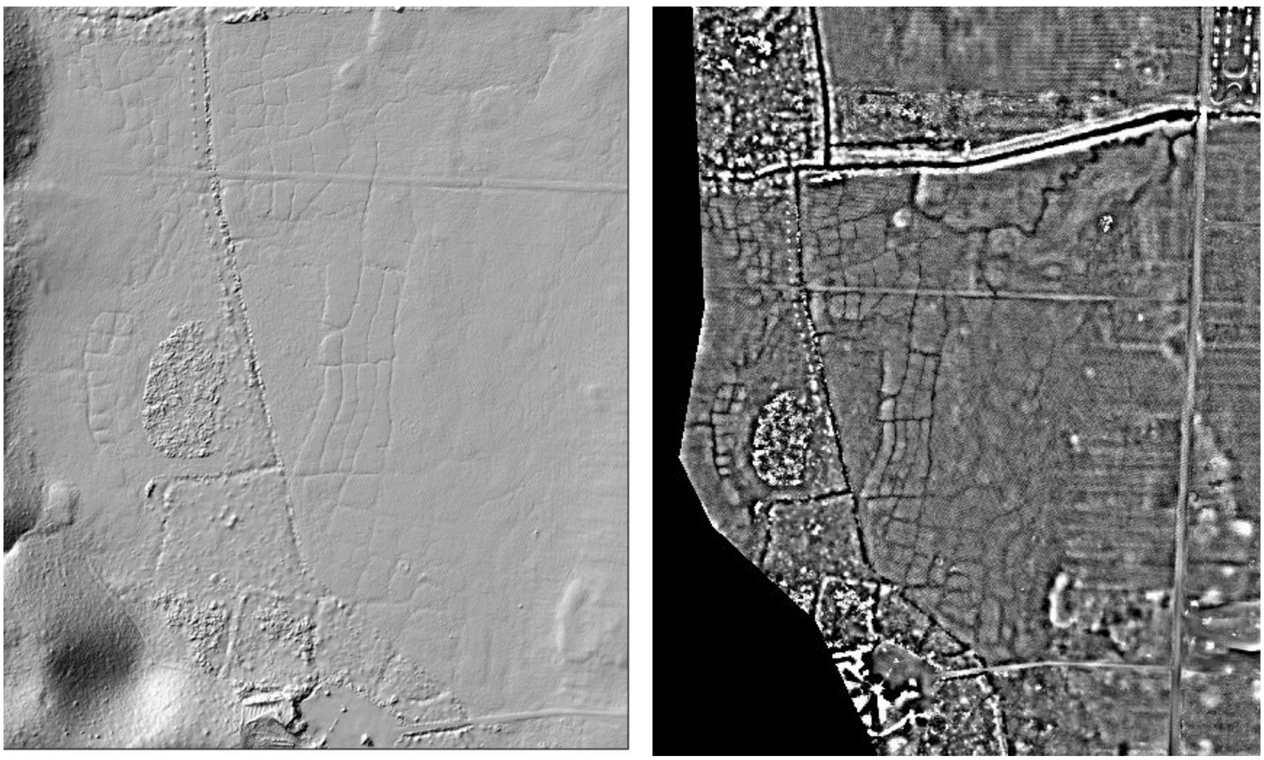

Figure 3.11. The well-studied Chan Cahal fields using the LiDAR DEM (left) and LiDAR DEM with a SLRM applied (right)

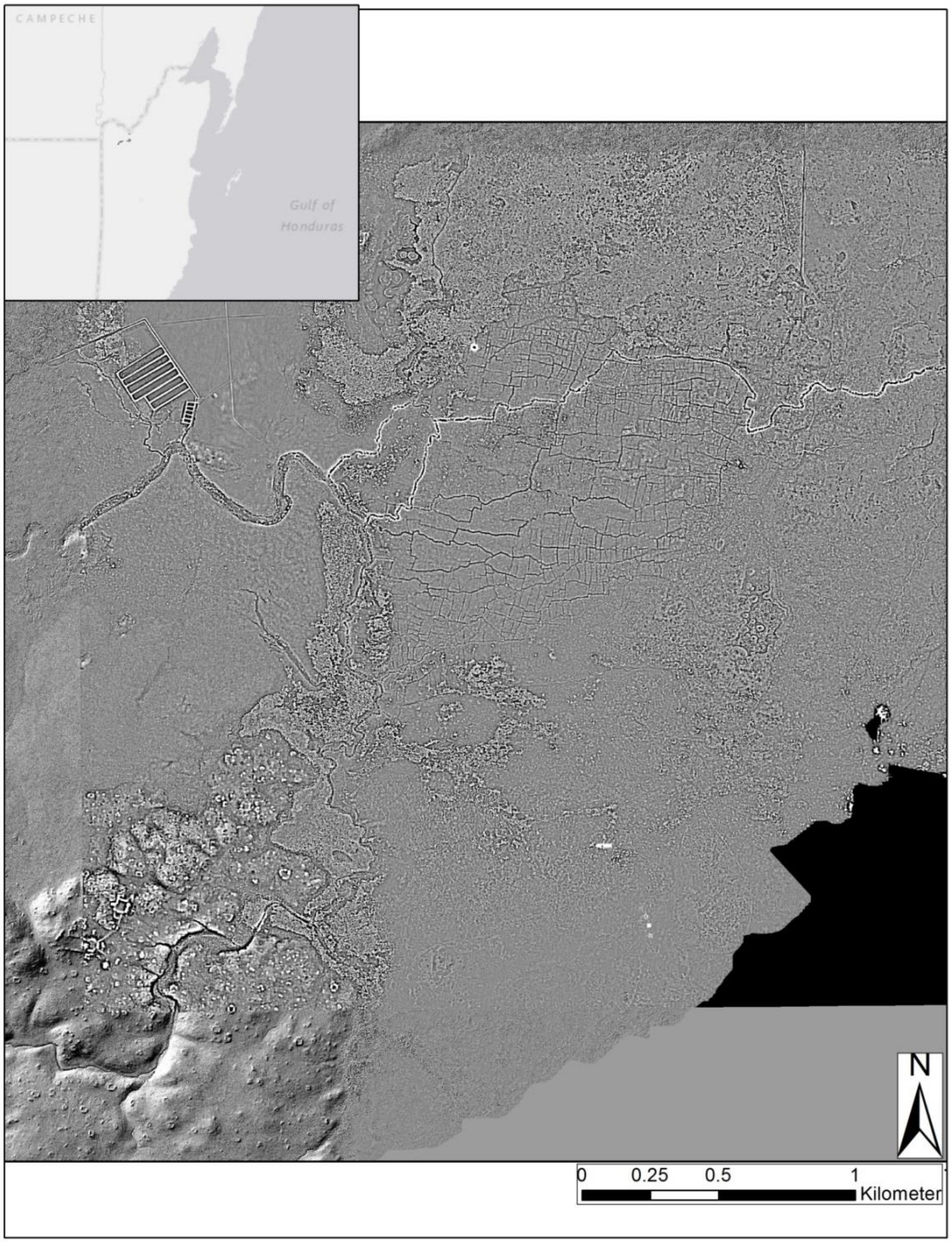

Figure 3.12. The Birds of Paradise system with a SLRM overlaying the agricultural canals and fields.

In addition to these new techniques, with the LiDAR data set it is now possible to create an automatic process by which I can extract anthropogenic features, in this case, canal systems, into a vector line file which can then be easily quantified in a GIS. This type of research will require more time and modeling, however this dissertation provides the preliminary work by which I can begin such an automatic quantification process. First, since the LiDAR dataset is so large and complex, it is necessary to clip the LiDAR DEM to the area of interest that the user wishes to extract features. Then, a SLRM is created of the clipped area using the RVT. Using ArcGIS Pro (for a more streamlined computational process), I created a 1x1 meter fishnet with surface information added (Mean Z). After the fishnet was created, I selected the grid cells with a value less than zero and exported it to a new feature, which captures the areas that are low enough to be considered anthropogenic canal features (Figure 3.13).

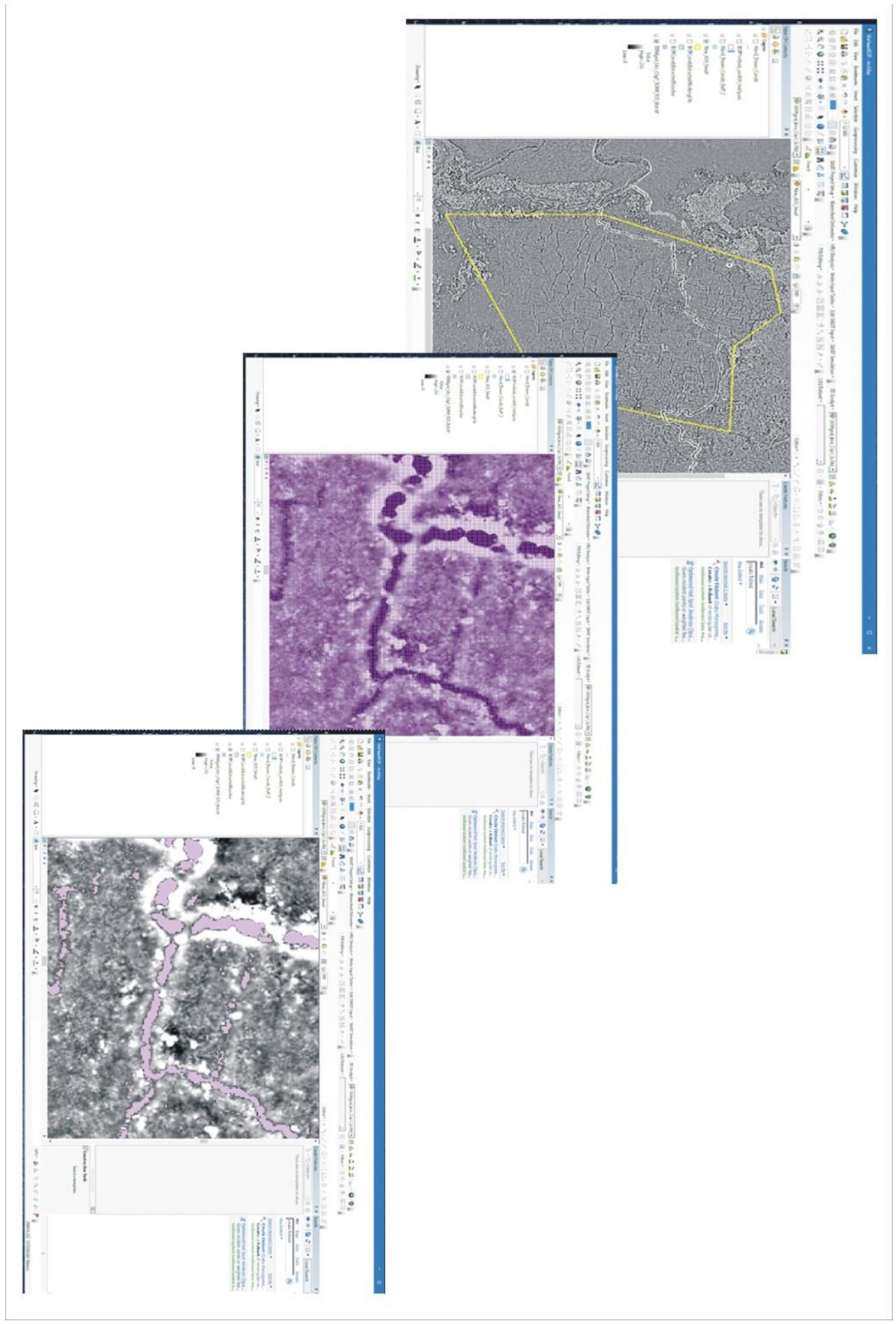

Figure 3.13. Extracting the canals to create a unique grid.

Using this technique, I was able to capture the majority of the canals within the Birds of Paradise system, and fully map the system based on both multispectral data and LiDAR data. Through the varied forms of remotely sensed data applied here, I have demonstrated that remote sensing is a valuable tool for archaeologists working within the Maya Lowlands and within regions beyond. As these techniques continue to refine, it will be possible to acquire more remote data regarding soil mineralogy, environmental quality, hydrological dynamics, and anthropogenic manipulation on a temporal scale. Remote sensing efforts are consequently still ongoing within the Maya Lowlands, and further field seasons should yield even more intriguing results.

Chapter 4: A Range of Agroecosystems: Multi proxies of Sierra de Agua and Neuendorf Wetland Fields[2]

4.1. INTRODUCTION

Scholors now recognize that prehispanic engineering resulted in significant modification of the soils, slopes, hydrology, and ecology of Neotropical wetlands and forests. Yet, we have only have a handful of studies that demonstrate this clearly (Beach et al., 2015a). Here I present two new examples of prehispanic Maya wetland agriculture from two different fluviokarst watersheds in the Belize, México, Guatemala transboundary region. Our goals are to identify long-term human impacts and adaptations in these tropical wetlands and provide new insights into Late Holocene geomorphology and soil formation. We hypothesize that Maya wetland agroecosystems in Central America were a large-scale endeavor and these systems dramatically changed geomorphology and soils at the regional scale, which has implications for ecosystem change and human adaptions over thousands of years. This paper tests this idea with multiple geoarchaeological techniques, including magnetic susceptibility, elemental geochemistry, stable isotopic changes through soil profiles, and soil stratigraphy. We then compare these new data with our previous work on the Chan Cahal wetlands, a major Maya agricultural zone in the Three Rivers Region of northwestern Belize. With this research, we expand the geographic footprint of our previous studies. Intensive

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[2] An edited and expanded Chapter 4 is currently (as of August 2018) in review in the Journal *Quaternary International* as part of a special issue entitled **Landforms and Palaeosoils**. I am the primary author and primary data analyst for this publication. I wrote most of the paper and I sampled soils, and analyzed them for a suite of geochemical proxies, including elemental geochemistry, stable isotopes, and organics. Coauthors and their roles on this publication are as follows: Timothy Beach, Sheryl-Luzzadder-Beach are experts in the region and provided support for fieldwork and fieldwork design. They also serve as PIs for funding sources, lab facilities and permits. Timothy Beach also provided writing, soil interpretations, and editing of the manuscript. Fred Valdez and Tom Guderjan serve as PIs for permits and gave minor edits, and Colin Doyle and Sara Eshleman served as field assistants and secondary data analysts for the publication. Steve Bozarth provided pollen analysis.

manipulations over large-scale environments range from demonstrable changes in erosional and depositional patterns (Anselmetti et al., 2007) to hydrological and ecological shifts (Mueller et al., 2010). We consider the multiple paths that ancient anthropogenic agents exerted and still exert over the system.

The old paradigms of intermittent swidden systems and small-scale specialized wetland gardens has shifted considerably in the field of geoarchaeology based on a growing corpus of studies to map and understand Maya canals and raised fields, as well as terraces, dams, and reservoirs in the Maya Lowlands (Turner 1974; Siemens and Puleston, 1972; Denevan 1980; Pope and Dahlin, 1989; Turner and Harrison 1981; Pohl et al., 1996; Dunning et al., 1999; Baker 2003, 2007; Beach et al., 2009). Early wetland field studies were based on the *chinampas* model from central México (Coe, 1964; Frederick, 2007), and we now increasingly understand Maya wetland engineering and morphology to be distinct and variable based on geography, water chemistry, soils, and cultural periods.

Maya wetland studies provide evidence for an early onset Anthropocene in the Neotropics (Beach et al., 2015b). Indeed, widespread landscape modification demonstrates that ancient populations acted as large-scale geomorphic agents and factors of pedogenesis that transformed erosional and depositional patterns across landscapes and modified hydrological systems (Beach 1998; Beach et al., 2015a). Regional wetland management during the Maya Preclassic (~3350-1750 years BP) and Classic (~1750-1000 years BP) times demonstrates a complex and fluctuating landscape with instances of degradation, sustainability, modification, and restoration. Our increasing understanding of these systems can provide us with an analog for modern wetland use and sustainability in the present day.

In this study we focus on two wetland systems situated within neighboring watersheds in northwestern Belize and synthesize our present findings with our previous case studies in the region (Figure 4.1). Neuendorf, sometimes called the Airport Fields (Beach et al., 2015a), is the first of these wetland field complexes. This system lies within the Three Rivers Region, just south of the Rio Azul, which forms the border with México. Neuendorf appears to have a hydrological connection with and certainly has similar geochemical characteristics as the Chan Cahal wetland fields (Luzzadder-Beach et al., 2009, 2012; Beach et al., 2015a). Sierra de Agua, the second study area, is a group of wetland field complexes near the ancient Maya city of Sierra de Agua, which lies about 40 km south of Neuendorf and within the New River watershed (Baker, 2003). To understand soils, human uses, and wetland field formation, we use a suite of geochemical, paleoecological, and geoarchaeological techniques to reconstruct the histories of the Sierra de Agua and Neuendorf systems, and then compare these models with previous models of wetland fields.

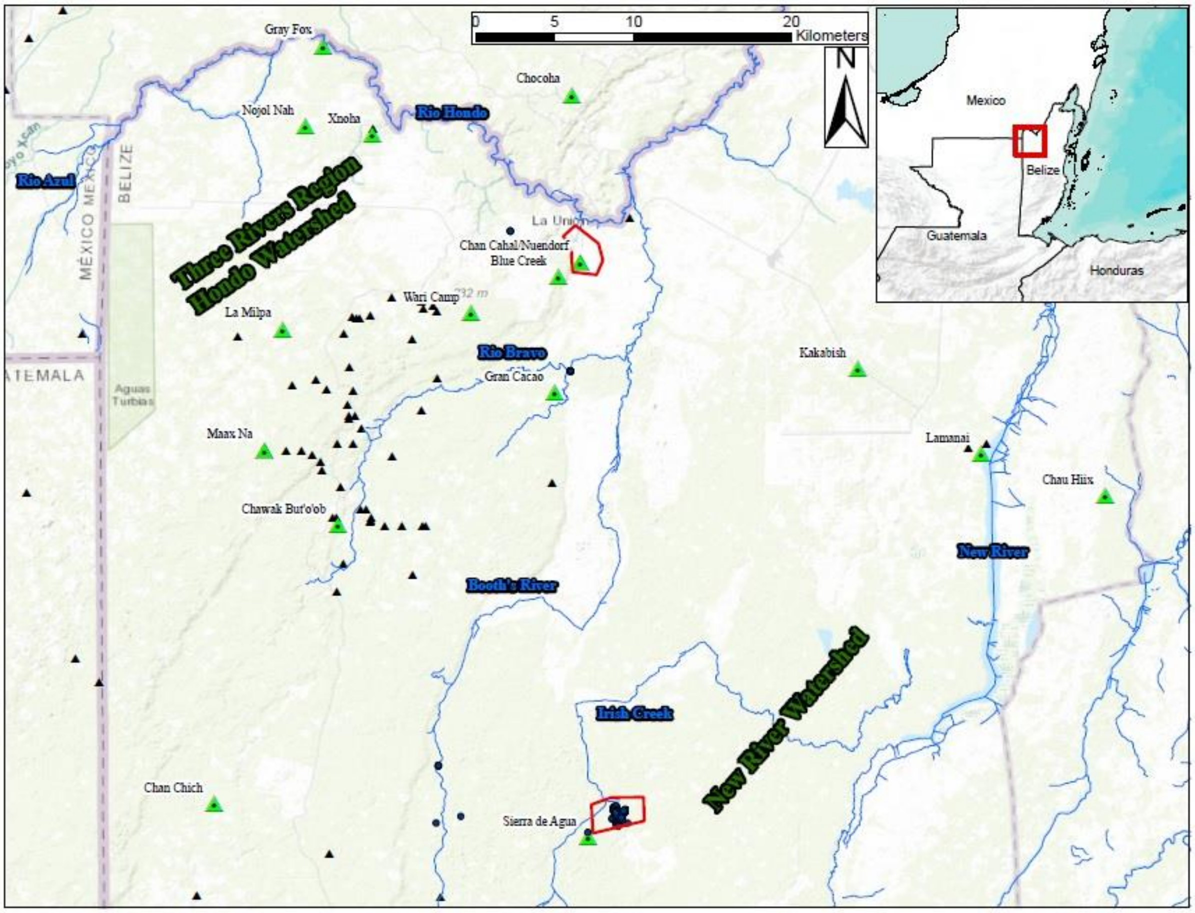

Figure 4.1. Chapter study areas.

Twenty years of research in the Chan Cahal wetland agroecosystem in northwestern Belize suggests intensive manipulation of wetland environments for agricultural purposes. Research at Chan Cahal has described the environmental history of the wetland field complexes using many Accelerator mass spectrometry (AMS) radiocarbon dates, carbon isotopic records, archaeological excavations, wetland cores, and phytolith and pollen studies (Luzzadder-Beach et al., 2009, 2012; Beach et al., 2011, 2015a). This multiproxy work showed evidence that construction of canals at Chan Cahal may have started in the Late Preclassic (2250-1750 years BP), though most evidence indicated Classic wetland field usage. This use persisted into the Terminal Classic (~1050 years BP) in some areas. On surrounding hillslopes, episodes of deforestation during Maya occupation accelerated erosion and tipped the geomorphic processes from dominantly karst to dominantly fluvial, creating prominent alluvial fans adjacent to preserved Maya canal systems (Beach et al., 2017a).

4.2. BACKGROUND/REGIONAL SETTING

4.2.1 Northwestern Belize

Our study sites lie on the edge of escarpments at about 20 m above sea level (masl) within the upper coastal plain in northwestern Belize, in the southern portion of the geographic and cultural region named the Maya Lowlands. The bedrock in this region is predominantly limestone and dolomitic limestone that range from Jurassic (King et al., 2003, 2004) to Quaternary in age (Perry et al., 2009). Some portions of the bedrock have variable quantities of chert (Beach et al., 2017a), which the ancient Maya exploited throughout their history for tool production (Shafer and Hester, 1983; Valdez and Aylesworth, 2005). Past tectonic activity in this region resulted in a series of normal faults that stair-step westward up to about 400 masl in the elevated interior region of Guatemala's Petén Department. The coastal plain is a low relief landscape of carbonate clays and inter-fingered sandplains with a range of wetland and low upland landscapes. Over the course of the Holocene, sea level rise has caused inundation and sediment deposition across this area.

Karst processes and landforms strongly influence watersheds in the region. Karstic features are prominent throughout both the uplands and lowlands, including isolated residual hills (*mogotes*), sinkholes (*cenotes*, *rejolladas*), and large-scale, low-lying depressions (*bajos*). Scholars have identified human engineered wetlands within most floodplains studied in the Maya region (Lambert et al., 1984; Seimens and Puleston, 1972; Luzzadder-Beach et al., 2008). Based on this growing evidence for ancient Maya agricultural wetlands, we hypothesize that riparian floodplains and the perennial and seasonal wetlands connected to them were critical components to Maya livelihoods.

Soils in the region have both autochthonous components from their five soil formation factors and allochthonous components from Saharan dust and volcanic inputs (Cabadas et al., 2010; Tankersley et al., 2016). The major soil order along the escarpments in northwestern Belize are Mollisols, often Haprendolls Great Group (Beach et al., 2017a, 2017b). These soils are limited agriculturally in that they are shallow and prone to erosion due to steepness and by tree-throw on natural slopes (Beach, 1998). In depressions, Histosols form where the water table is nearly perpetual and Vertisols form where the water table is below the surface and soils formed for a few thousand years (Solís-Castillo et al., 2013). Some of the depression sequences can be many m thick, especially where multiple erosional events have deposited many layers of soil from adjacent escarpments. In wetlands, often there is a secondary precipitation of biochemical calcite as well as an accumulation of organics (Sedov et al., 2008) accompanied by surface accumulation of algal residues.

There has been some work on Anthrosols throughout the region, specifically within ancient cities like Chunchucmil (Beach et al., 2017b) and at local scales within coastal sites, such as Marco Gonzalez (Graham et al., 2017). We still know little about scope and scale of Anthrosols in Central America unlike the Dark Earths of South America, which many studies link to agricultural intensification and settlement (Myers et al., 2003). Within in many depression soils in this region is a facies change from a stable soil surface aggraded sediments often called “Maya Clay” lying above a paleosol. Scholars first started using ‘Maya Clay’ for phyllosilicate clays dating to the Maya period from 4,000-1,000 years BP in lake sediments, sandwiched between earlier and later organic sediments (Beach et al., 2015a). The term ‘Maya Clay’ refers to fine grained sediment, often montmorillonitic, commonly with abundant cultural materials and elevated phosphorus, deposited as early as 4000 years BP due to human induced erosion, perhaps coupled with regional drying (Jacob and Hallmark 1996; Brenner et al., 2002; Anselmetti et al., 2007; Luzzadder-Beach et al., 2009).

Two major water chemistries influence this region. First, meteoric inputs and runoff from uplands with low dissolved loads, and second, groundwater from spring sources with a high TDS that is rich in sulfur and calcium. Levels of total dissolved solids, calcium, and sulfur fluctuate within both surface and groundwater across the region, and undiluted groundwater at escarpment edges often has the highest solute loads (Beach et al., 2017). Water chemistry is a necessary component to this research, because Maya wetland field and canal agroecosystems require water quality and availability that differs seasonally. Luzzadder-Beach et al., (2016) hypothesized that ancient Maya canal building was a complex system of water diversion and/or storage depending on quality and quantity of ground and surface water at different times.

The modern climate of northwestern Belize is tropical with a rainy season between May to December and a pronounced dry season from January to April (Gamble and Curtis, 2008). There is also a minor, “canicular” drought in July or August (Gamble et al., 2008). Precipitation drivers in northwestern Belize include fluctuations of the Inter Tropical Convergence Zone (ITCZ) and subtropical high pressure, the positioning and strength of the easterly trade winds, and tropical storms (Boose et al., 2003; Beach et al., 2017a). The average summer temperature generally ranges between 31˚C to 22˚C, and winter temperatures range between 28˚C to 18˚C (King et al., 1992). Vegetation in northwestern Belize follows an elevation gradient, with uplands generally supporting a tropical forest of about 50 tree species per hectare (Brokaw et al., 1993; Brewer and Webb, 2002), while the lower coastal plain supports a less diverse community.

4.2.2 Wetland Agriculture and the Maya

The ancient Maya and their predecessors inhabited this landscape from before the Holocene (prior to 11,600 years BP) (Valdez and Aylesworth, 2005) through the Terminal Classic (~1050 years BP), and in some instances, expanding into the Historic period (Graham 2004). Today, population studies estimate that about 6 million Maya speaking people still live within the Guatemala, Belize, México transboundary region (Beach et al., 2015b).

During the Archaic period, deforestation and agriculture are visible in the archaeological record only on a site-by-site basis (Jones, 1994; Pohl et al., 1996; Beach et al., 2015b). Detectable settlement and monument building across the Maya Lowlands began in earnest around 2,950-2350 years BP, during the Early Middle Preclassic (Guderjan, 2004). By the end of the Late Preclassic (1750 years BP), some archaeological records show a noticeable decline in some urban centers and a political/population shift to new centers. This correlates to significant regional drying in the region at this time (Medina-Elizalde et al., 2016). Population and urban activity increased again during the Early Maya Classic (1650-1350 years BP) after political reorganization. Extensive archaeological work on urban zones suggests the Late Classic period (1400–1100 BP) had the highest population and the most widespread and intensive agriculture until about 1200-900 BP (Guderjan et al., 2009; Valdez and Scarborough, 2014). After this florescence, most urban centers were depopulated, and the cultural patterns of the Maya dramatically changed in subsequent periods into the Colonial period (Graham, 2011).

There are now many models of how and to what extent the Maya modified wetland environments throughout their occupation. Taken together, we can consider the Maya as active geomorphic agents that widely modified soil development. Seimens and Puleston (1972) have documented extensive canal systems across the Rio Candelaria floodplain. Turner and Harrison (1981) documented a series of large-scale terraces over a 10,000 square kilometer area in the Rio Bec region of the Mexican states of Campeche and Quintana Roo. In the 1980s, researchers estimated that that there were at least 3,200 hectares of anthropogenically modified drained or raised field systems within these wetland systems in the Rio Hondo watershed on the Belize/México border (Seimens, 1983). Modification in the form of drained fields, dams, and canals have also been studied along the New River near the major Maya site of Lamanai (Lambert et al., 1984) and within the Belize River watershed bear the Maya site of Chau Hiix (Pyburn, 2003; Harrison-Buck, 2014). Within the Three Rivers region, Luzzadder-Beach et al., (2012) and Beach et al., (2015a, 2015b) have documented wetland fields within diverse geochemical settings, suggesting different cultivation and agricultural strategies based on geographic location. Guderjan and Krause (2011) have also documented extensive canal systems along the entire length of the Rio Hondo through aerial survey and remote sensing.

4.2.3 Neuendorf/Three Rivers Region

The Neuendorf wetland system, called the Airport Fields in previous publications (Beach et al., 2015), lies in the Three Rivers Region. Here, three principle drainages flow into the greater Rio Hondo watershed that then flows northeast and empties into the

Caribbean. These three tributaries, Rio Bravo, Rio Azul, and Booth's river, make up a largely perennial, fluviokarst basin. Cenotes and upland bajos and springs also serve as groundwater sources here. The Neuendorf wetlands are seasonally wet systems that lie directly below the Rio Bravo escarpment, which is the easternmost prominent scarp formed by the larger system of normal faults that stretches from the Caribbean of Belize to the central Petén of Guatemala. Neuendorf is adjacent to the Chan Cahal/Sayap Ha settlement and field system, located about 1.2 km south and west (Beach et al., 2015a).

Small, unexcavated house mounds lie scattered throughout the Neuendorf fields on raised platforms to the east of the Bravo Escarpment for about 1.5 km. This settlement may be part of the northern extent of the greater Chan Cahal community and the elite polity of Blue Creek, which was active from the Middle Preclassic to the end of the Classic (2900 to 1000 BP). The timeline of Blue Creek's occupation was derived from ceramic sequences and extensive excavations within public structures within Blue Creek's site core (Guderjan, 2004). The major public architectural components of Blue Creek are located ~100 m above the wetland complex on the crest of the Bravo escarpment. The community of Chan Cahal, like Blue Creek, was generally active for 2 millennia, from as early as the Early Middle Preclassic to the Late/Terminal Classic. These chronologies derive from both ceramic typologies and many radiocarbon dates collected in previous excavations (Beach et al., 2015a).

Phytoliths and macrobotanicals from previous excavations include maize (*Zea mays*), squash (*Cucurbita* spp.), avocado (*Persea americana*), beans (*Phaseolus* spp.), sapodilla (*Manilkara zapota*), and even cacao (*Theobroma cocao*) (Bozarth and Guderjan, 2000, Beach et al., 2015a). This previous research on cultigen within soil sequences in the Chan Cahal complex demonstrates the importance of the ditched fields to local farming. We have also studied the agricultural patterns of the Sayap Ha settlement, which lies a few m below and several hundred m southwest of Chan Cahal. This settlement may again be part of the community of Chan Cahal (Beach et al., 2015a). Our regional research has also expanded into testing north of Chan Cahal into the Neuendorf settlement and eastward into untested archaeological settlement zones. These studies strive to enhance our knowledge of human modification and natural formation of these wetlands, temporally and spatially.

Previous studies demonstrate long-term anthropogenic manipulation within the Chan Cahal/Sayap Ha wetlands in the Three Rivers Region. Beach et al., (2009; 2015a) developed the following five-stage conceptual model of Maya agroecosystem formation. Before 4000 years BP, Archaic farmers grew dryland crops in this area. Sometime after this in the Preclassic (3000 to 1700 BP) water table rise inundated the area, indicated by Histosols forming above the basal mineral Vertisols. The third stage of development began when gypsum began to precipitate and the soils began to aggrade due to erosion from the Rio Bravo escarpment directly upslope and throughout the watershed caused by Preclassic Maya deforestation. During the Classic Maya period, the fourth stage of wetland development began, as the farming community began to build extensive canal systems into the wet landscape and dredging the canal sediments on top of the agricultural fields. The fifth stage occurred when canals began to aggrade around 1100 years BP, suggesting Maya or canal-maintenance abandonment. From the Terminal Maya Classic to today, this system is a wetland with the water table near the surface perennially but drier from January into May. Modern farmers have maintained pasture and cattle grazing in the canal-drained landscape since the late 1950s.

Our previous excavations at Chan Cahal and the surrounding wetlands in Sayap

Ha and Neuendorf include trenches and pits dug into an earthen platform, agricultural fields, and within agricultural canals. Further, using a vibracoring system, we collected sediment cores from a Maya reservoir located in the center of the Chan Cahal canals, as well as additional cores from fields within the system. We obtained AMS dates from all of these excavations and cores to develop a model for sedimentation and wetland development. We also analyzed pollen and carbon isotope profiles from these excavations to better understand land conversion and crop diversity during Maya occupation.

Vibracores of various sediment sequences from the 2011 and 2012 field season at Chan Cahal (Beach et al., 2015a) support our working model of wetland formation. One of these vibracores came from the reservoir within the Chan Cahal fields, and two other vibracores came from raised wetland fields. The first field core contained 117 cm of sediment and provided a bottom date of 2,379+/-30 (or 2 σ Cal BC 724-391) within an organic rich (2.5YR 5/4) sandy layer. Above this in the sequence were layers of clay loams and hemic peats with fine masses of gypsum. The second field core was 184 cm deep with a paleosol that extends from the bottom of the core to a depth of 174cm. Above this paleosol in the second field core, we encountered similar gypsum rich clays and hemic peat layers. The bottom paleosol, which we call *Ekluum* (Maya term for Black Earth) (Dunning and Beach, 2004), recorded an age of 2690 +/-30 years BP (or 2 σ Cal BC 900 to 800) in a parallel sequence in the reservoir vibracore. These sequences within our wetland field and reservoir cores follow our model of a stable terrestrial surface inundated sometime during the Middle to Late Preclassic, which formed layers of peats and clays above. We interpret the presence of gypsum in these sequences as naturally precipitated from Ca and SO_4 perhaps during dry seasons when high evaporation led to saturation (Beach et al., 2009; 2015a). There was relatively less gypsum within the reservoir core than the field cores, probably due to consistent inundation, which minimized Ca and SO_4 saturation and gypsum precipitation.

4.2.4 Sierra de Agua/New River Watershed:

Wetland fields in the SDA were first photographed by N. Brokaw in 1992 (Baker, 2003). This system of fields and archaeological mounds is remote and only accessible by a main road that has infrequent maintenance. Intermittently open logging roads provide access from the main road, which provided two phases of access in the 1990s and 2011. The wetlands in this area connect hydrologically to the Irish Creek swamp, which drains into the New River and travels northeast until it empties out into Chetumal Bay. The significance of this watershed culturally is its connection to persistent Maya urban centers along the river system. These Maya centers include Lamanai, which was an occupied Maya Center from the Early Preclassic until the Historic period (Powis et al., 2009; Thornton, 2011), and Cerros, a known trade center at the coast that persisted from the Late Preclassic until the Postclassic time period (Robertson et al., 1986). The Irish Creek swamp lies at about 30 masl. The wetlands in this area range from small depressions that are intermittently flooded to perennially flooded sinks associated with springs.

Baker excavated in the Sierra de Agua wetlands in 1995 and again in 1997. These totaled five excavations, four in agricultural features (ditches and field platforms, and within a dam) and one excavation adjacent to a Maya house-mound. Although most of the cultural material recovered from these excavations was undiagnostic, Baker reported three distinct ceramic types: Tinaja Red, Achote Black, and Cayo Unslipped, all dating to the Late and Terminal Classic Periods (Baker, 2003). This excavation also provided a radiocarbon date on a paleosol dating to 1265 or 2 σ Cal BC 1490 – 940 (Beach et al., 2003). A pollen core taken in the wetlands provides evidence for maize and manioc in the Late Classic, which was followed by reforestation, probably due to abandonment of the agricultural system and by extension; the urban center (Dunning et al., 2003).

4.3. MATERIALS AND METHODS

4.3.1 Soil Pits and Trenching:

Our main goals for this study were to use soils and multiproxy geoarchaeology methods to understand ancient Maya wetland field formation, morphology, and use over time. Toward these ends, we excavated four new units from the Three Rivers Region and the New River Watershed. These include two hand-excavated trenches in Sierra de Agua: unit 1 (SDA1) in a natural wetland and unit 2 (SDA2) in the heart of a wetland field surrounded by ancient but still flowing ditches. For Neuendorf in modern pastureland, we backhoed two trenches: trench 1 (T1) through an ancient Maya canal and field system and trench 2 (T2) through an upslope alluvial fan to understand role of hillslope sediments on wetland fields (Figures 4.2 and 4.3). These trenches filled with groundwater quickly due to proximity to the water table. We developed chronologies for these soil profiles by collecting artifacts and radiocarbon samples systematically throughout the profiles, and identified the soil horizons in each unit using Munsell color, field texture, and soil structure. Using a SM20 magnetic susceptibility meter, we collected field measurements of magnetic susceptibility (10^{-3} SI units) on flat soil surfaces in 5 or 10 cm increments over each soil horizon within the trenches and then sampled the exposed profiles by horizons.

4.3.2 Vibracoring

Vibracoring is a technique used for collecting sediments with a tube motorized to vibrate rapidly (Smith, 1992). The benefit of vibracoring as a technique is that, instead of other traditional coring methods, the vibracore penetrates using continuous vibration rather than percussive forces or rotation, which lessens the possibility of contamination or loss of soft or muddy sediments. This aids in sampling deeper sequences with less potential disturbance (Smith 1984). Vibracoring works best in places like our study area with saturated organic sediments, clays and silts, and previous research suggests that the method is not efficient within coarse textures (Bhadha and Jawitz, 2010). We extruded cores in our field station, sampling only the inner sections of cores, away from the edges where mixing can occur. We discuss and provide new data from three of our vibracores here as directly relevant to wetland field formation, chronology, and use. These include two cores (1 and 2 in 2011) through the middle of fields in Chan Cahal and a third (Chan Cahal canal core in 2012) through a canal near the Neuendorf field. We use the Chan Cahal canal core to understand the stratigraphy of the Neuendorf canals between fields because Neuendorf T1 and T2 filled too quickly with water in the canal zone, which we dammed off to maintain unit integrity.

4.3.3 Laboratory analysis:

Beta Analytics ran Accelerated Mass Spectrometry on radiocarbon samples from our excavations and cores. We sampled wood, peat, charcoal, or organic sediments from discrete strata to provide material for dating, reported as calibrated at the two sigma (95% probability) level.

We performed a battery of geoarchaeological and paleoecological tests on all of these soil sequences, including magnetic susceptibility, texture, X-ray Fluorescence, pH, and

Mehlich II to quantify extractable phosphorus (Table 4.1). We also analyzed pollen from SDA2 (Figure 4.5). Two labs provided soil testing using the same methodology: the Brigham Young University Geochemical Soil Analysis Laboratory or the Soils and Geoarchaeology laboratory at the University of Texas at Austin.

We measured extractable phosphorus from each of the soil horizons in our excavations. Several previous articles describe the Mehlich II method (see Beach et al., 2017a). This method performs well for extractable phosphorus analysis because P, a light element, is often difficult to detect using other instruments. We determined the extractable P from soil samples using a Hach DR/850 Colorimeter on the percent transmittance function at a wavelength of 690 nm (Terry et al., 2000). We then used a standard curve with known P concentrations from which we calculated each sample's phosphorus concentration. Using X-ray Fluorescence (XRF), we determined the inorganic geochemistry of each pit. We also tested the pH of each strata using a Hach pH instrument.

We calculated stable carbon isotope ratios for each strata by reducing the sub samples to the humin fraction. Previous studies in the Maya world (Webb et al., 2004) demonstrate that the humin faction of a soil is the most sensitive faction for detecting changes in C_4 vegetation. First, we removed the humic and fulvic acids of each sample using standard methodology (see details: Webb et al., 2004; Fernandez et al., 2005; Beach et al., 2017a). Second, samples were combusted in an Isotope Ratio Mass Spectrometer (IRMS). This combustion converts the humin fraction to CO_2 and introduces it into the IRMS. We measure the ratio of the isotopes ^{13}C and ^{12}C for each given sample and report the isotope ratio as $\delta^{13}C$ values with the ‰ unit against VPDB (Vienna Pee Dee Belemnite). Values of $\delta^{13}C$ can increase naturally through soils due to processes such as microbial activity (Webb et al., 2004, 2007), and generally we can attribute an increase or shift < 3.5‰ to natural bioturbation. We attribute a shift of 3.5 ‰ or greater to vegetation change, possibly to an effect that signifies a shift towards widespread agriculture.

4.4. RESULTS

4.4.1 Trenches at Neuendorf Alluvial Fan and Wetland Field

We placed the two backhoe trenches within the Neuendorf wetlands strategically through two different depositional systems. T1 cuts through a Maya canal and field system in a floodplain wetland, while T2 cuts through an adjacent footslope of an alluvial fan. Beach et al., (2017a) presented the alluvial fan excavation as part of a regional study on hillslope erosion and stability, and here we synthesize this work along with new geochemical data as part of our efforts to understand the alluvial fan and how it compares to wetland genesis and soil development surrounding the Chan Cahal wetlands.

T1 (Figure 4.2), through the ancient Maya field, reached a depth of 2 m, which was the level of the water table in late dry season. This trench cut across two raised fields, but the soft, water-rich sediments in the canal portion were left unexcavated to preserve the unit's structural integrity. Soil horizons started from the thin O (10 YR 2/2, very dark brown) in the upper 0-2 cm of soil across the field zone. It is composed of a dark, organic-rich, silt loam. The A horizon (10 YR 2/1, very dark gray) spans the next 2-14cm. This soil is generally lighter than the O horizon above, with small gypsum masses and larger roots throughout.

Table 4.1. Soil horizons and geochemistry for Neuendorf and Sierra de Agua Pits.

Soil profile	Depth		Horizon	Soil Color	$\delta^{13}C$	MS 10^{-3} SI	pH	%TOC	P
	cm			Moist	%			%	mg/Kg
Nuendorf Field (T1)									
	0	2	O	10 YR 2/2	-18.62	0.08	7.2	35.17	0.623
	2	10	A	10 YR 2/1	-24.05	0.06	7.2	16.24	0
	14	95	C	10 YR 4/1 dark gray to 10 5/1 gray with 7.5 YR 4/6	-26.42	0.03	7.8	8.7	0
	95	130	Cgy	10 YR 4/1	-25.3	0.05	7.7	8.5	0
	130	155	Aby	10 YR 2/1	-27.13	0.04	7.7	8.67	0
	155	180	Aby/Ab2	10 YR 2/1	-27.13	0.07	7.7	6.63	0
	180	200	Ab2	10 YR 2/2	-27.52	0.19	7.7	20	0
	200+		Cg	(grey green)					
Nuendorf Fan (T2)									
	0	20	A	10 YR 2/1	-20.44	0.53	7	12.44	13
	20	45	A2	10YR 4/1	-22.93	0.07	7	7.69	2.8
	45	100	C	10 YR 5/1	-23.14	0.10	7.8	7.05	0.9
	100	145	Ab	10 YR 3/1	-24.02	0.06	7.7	6.11	1.1
	145	170	2Cb	7.5 YR 5/8 to 7.5 YR 6/8	-25.45	0.18	7.7	4.42	2.4
	170+		Ab2	10 YR 2/2	-26.91	0.11	7.7	21.71	3.2
Sierra de Agua Unit 1									
	0	7	O		-	-	-	-	-
	7	20	A	2.5 Y 2/0	-27.91	0.023	6.9	8.91	9.18
	20	40	Acgy	10 YR 6/8 + 7/8 and 2.5Y 3/0	-23.09	0.078	6.6	0.34	3.61
	40	120	Cgy	10 YR 8/1 and 5G 6/1	-25.58	0.109	7	0.67	4.46
	120	150	Cgy2	5G 6/1	-27.21	0.11	7.1	0.21	5.8
Sierra de Agua Unit 2									
	0	11	Oe	10 YR 2/2	-	-	-	-	-
	11	23	Cy	10 YR 7/1 and 10YR 6/8	-27.95	0.03	7.1	1.41	5.58
	20	50	Acgy	10 YR 6/8 + 7/8 and 2.5Y 3/0	-27.22	0.03	6.7	3.32	5.4
	50	70	Oa	10 YR 2/2	-28.37	0.052	4.7	11.72	6.43
	70	120	ACg2	5Y 4/1	-22.62	0.046	6.2-6.8	2.68	6.11
	120	140	clasts	-	-20.92	0.041	-	-	5.58
	140	170	Oab/Ab	5Y 2.5/1	-19.45	0.058	4.7 to 6.4	9.74	5.47

The Cy horizon (10 YR 4/1 dark gray to 10 5/1 gray with 7.5 YR 4/6) spans 14-95 cm, and shows a downward increase of yellow mottling and a distinct increase of fine gypsum. Usually dating soils does not provide chronologies of soil formation, but experience in this environment showed that many soils are periodically aggrading. We dated charred organics at 76 cm within the C horizon to an age of 1290-1355 years BP. A wavy boundary separates the C from the next layer, a Cgy horizon (10 YR 4/1 with white gypsum masses) that ranged from 95-130 cm. This horizon has mottling of gray and white with small inclusions of yellow and many pockets of oxidation features. The white mottles are gypsum and increase with depth. We dated burnt material in the Cgy horizon at 120 cm to 1310-1410 years BP. Below this is a poorly developed Aby horizon (10 YR 2/1) spanning from 130-155 cm with decreased yellow mottles (7.5 YR4/6, strong brown) but still increasing gypsum. Below this, we define a transition zone between 155 to180cm, which is a darkening gray with large inclusions of sascab (saprolitic limestone) (Darch, 1981), yellow mottling, and small snail shell (*Pomacea flagellata*). Below this to a depth of 200+ cm the soil profile transitions to the Ab2 horizon, which Beach et al., (2009) referred to as the *Ekluum* paleosol. This paleosol is a dense, black clay with numerous large and small terrestrial and intermittent wetland mollusk shells. We did not obtain a radiocarbon sample from this horizon, but previous excavations produced AMS ages that ranged from 2100 to 3300 cal yr BP (Luzzadder-Beach and Beach, 2009) and one AMS age from the Ab2 horizon 20 m away from this site was 2640 +/- 30 BP (Table 4.2, Figure 4.2). The top of the Ekluum paleosol here is thus from the Maya Middle Preclassic, which is close to the earliest occupation at Chan Cahal (Beach et al., 2015a). We found many undiagnostic ceramics and lithic flakes from the O horizon to the top of the Ab2 horizon.

T2 had no O horizon, probably due to burning and deforestation. The surface horizon here is a relatively thick, very dark gray, A horizon (10 YR 2/1) that extends downward to about 20 cm. This silt loam horizon contains many fine roots and has granular structure. Below this, the A2 horizon (10 YR 4/1, dark gray) reaches a depth of about 45 cm, and contains sub rounded to sub angular chert inclusions within a clay matrix. The chert inclusions range from pebble to cobble in size. Below this, the horizon gradually transitions to a C horizon (10 YR 5/1, gray), which extends to 100 cm. This C horizon contained larger clasts of rounded to sub rounded chert and limestone. This could represent a higher energy layer of alluvial activity. Below this from 100-145cm was a slightly darker (10 YR 3/1) Ab horizon that contains small masses of carbonate and slightly smaller chert clasts. At 116 cm in the Ab horizon, charred organics produced an age of 1565-1715 cal yr BP. Below the Ab horizon, was a 2Cb horizon from 145 to 170 cm that is a highly oxidized, high-energy deposit of large sub rounded to sub angular chert and limestone cobbles and an oxidized clay matrix with mixed colors from 7.5 YR 5/8 (strong brown) to 7.5 YR 6/8 (reddish yellow). At 160 cm in the 2Cb charred organics produced a date of 1990-2145 years BP. Below a depth of 170+ cm was the Ab2 or Eklu'um Paleosol, again with many mollusk shells of various sizes. We again found many undiagnostic ceramics and lithic flakes from the top horizon to the top of the Ab2 horizon.

Table 4.2 Radiocarbon Dates.

Sample #	Site	Horizon	Depth (cm)	Material	Conventional Age	δ13C (‰)	2 σ ADBC
Vibracores*							
UA AMS Lab 2173	Chan Cahal Field Core 1		80cm	Organic Soil	1940 +- 36	-19.2	BC 36- AD 130
UA AMS Lab 2162	Chan Cahal Field Core 1		114-117 cm	Hemist Peat	2,379+-30	-26.7	BC 724-391
UA AMS Lab 2193	Chan Cahal Field Core 2		41 cm	Carbon	744 +-35	-26.5	AD 1219-1294
UA AMS Lab 2208	Chan Cahal Field Core 2		117 cm	Carbon	2310 +-46	-22.1	BC 507-207
WH116665	Chan Cahal Canal Core		62cm	Organic Soil	Modern		
BETA 382207	Chan Cahal Canal Core		103cm	Organic Soil	1870 +/- 30	-25.9	Cal AD 75-235
WH116666	Chan Cahal Canal Core		146 cm	Organic Soil	1950 +/- 35		Cal BC 36- AD 126
WH116667	Chan Cahal Canal Core		180 cm	Organic Soil	2550 +/- 30		BC 800-549
Neuendorf Trenches							
BETA 2-2016-19	Nuendorf Fan	Ab	116cm	Carbon	1740 +/- 30 BP	-25.5	Cal AD 235 to 385
BETA 2-2016-10	Nuendorf Fan	2Cb	160cm	Carbon	2090 +/- 30		Cal BC 195 to 40
BETA 2-2016-6	Nuendorf Field	C	76cm	Carbon	1420 +/- 30	-23.4	Cal AD 595 to 660
BETA 2-2016-7	Nuendorf Field	Cgy	120cm	Carbon	1480 +/- 30	-24.4	Cal AD 540 to 640
BETA 2-2016-8	Nuendorf Field	Ab2	180cm	Carbon	1680 +/- 30	-26.6	Cal AD 260 to 280 and Cal AD 325 to 420
Sierra de Agua Pits				Carbon			
UA AMS Lab 2128	Sierra de Agua Unit 2	Oa	50cm	Carbon	1304 +-35	-27.4	AD 658-769
UA AMS Lab 2139	Sierra de Agua Unit 3	Oab	149cm	Carbon	3,107+-38	-19.3	BC 1447-1264
UA AMS Lab 2138	Sierra de Agua Unit 4	Ab	170cm	Carbon	3,349+-33	-25.5	BC 1877-1661

*Previously Discussed in Beach et al 2015a

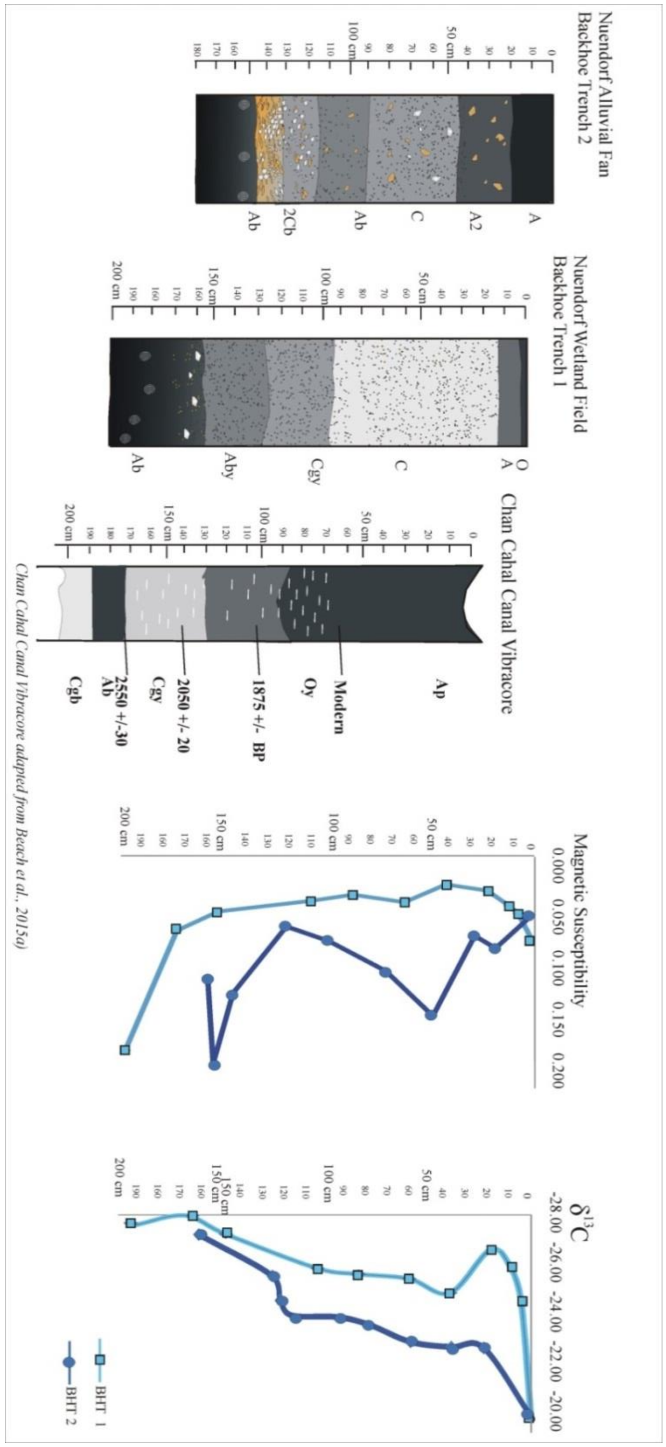

Figure 4.2. Neuendorf trench stratigraphy, magnetics, and carbon isotopes.

We analyzed these trenches to determine trends in magnetic susceptibility, inorganic geochemistry, and carbon isotopes. Magnetic susceptibility is highest in both trenches within the Ab2 paleosol, and steadily decreases up the profiles. In the wetland field in T1, the paleosol also contains a relatively high amount of Al and Si, and this too decreases with decreased depth, while S and Ca increase higher in the profile. P is low throughout the wetland field, except in the top portions of the profile, due to modern fertilizing. In T2, Al, Si, and S are relatively low throughout the profile, while Ca is consistently high. P increases within the paleosol in BHT2 but is low within the depositional layers, only increasing again at the surface. The $\delta^{13}C$ value for the paleosol in both field and fan is -27 ‰, which reflects the C_3 forest in the Middle Preclassic. Both profiles exhibit an upward trend toward less negative $\delta^{13}C$ values, demonstrating a shift from tropical forest towards tropical grasses. There is a slight reversal around 30cm towards more negative numbers, which then trends to their highest positive levels near the surface.

4.4.2 Vibracores and Pollen Analysis from the Chan Cahal System

To understand wetland field formation at Neuendorf, we use a new pollen sequence from a vibracore placed in nearby Chan Cahal Field 1 (Figure 4.3). Because the field 1 and 2 had the same stratigraphy and similar dates, we used AMS dates from these adjacent fields to better resolve the chronology of field formation and uses (Beach et al., 2015a). We interpret a four-part division of the core record. First, below 170 cm is a wetland paleosol that dates to the Middle Preclassic and earlier. Second, from 169 to 80 cm, in the later Preclassic, there is an increase in aquatic species and offset spikes of large and small charcoal. Third, at about 80 to 60 cm is the Classic period with an increase in *Zea Mays* and charcoal. The fourth zone is the post abandonment to recent disturbance from modern farming.

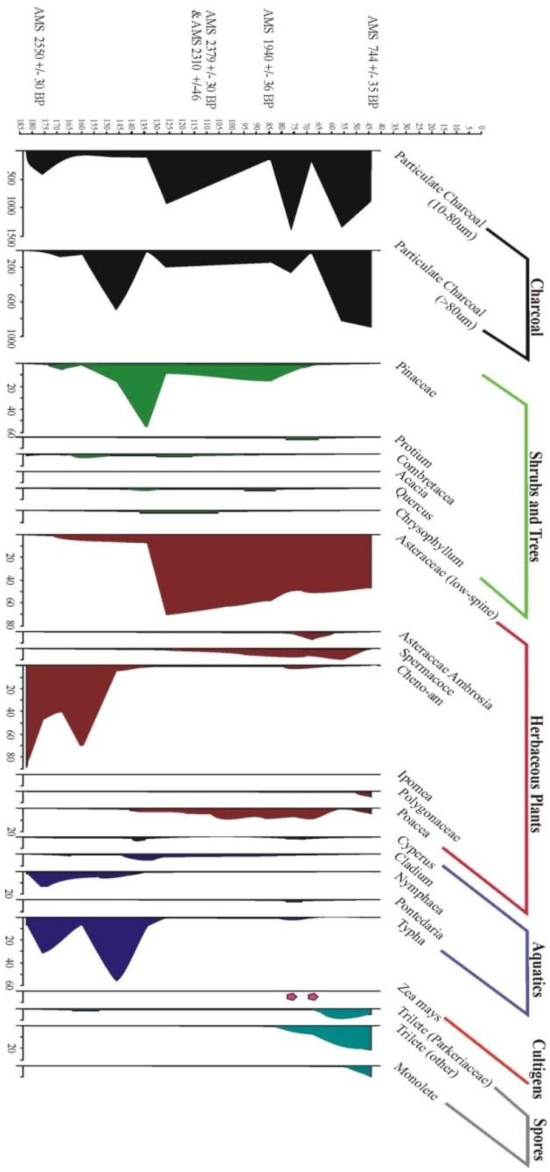

Figure 4.3. Chan Cahal pollen.

The first zone, from 182 to 170 cm, is a black, organic-rich clay with copious mollusks. This layer had excellent pollen preservation that was dominated by the disturbance taxa of chenopodium/amaranth, some aquatics like *Typha* and *Nympha*ea. There was no large charcoal (<80 µm) but there was a sizeable concentration (2,000 to over 4,000) of charcoal smaller than <80 µm. An AMS date in core 4 from this level dates the paleosol at 2550 +/- 30 BP, which aligns with earlier dates from the top of the paleosol that range from the Middled Preclassic to the Late Archaic (Luzzadder-Beach and Beach, 2009). The dominance of disturbance species at this level, the presence of Maya architecture at Chan Cahal, and *Zea mays* pollen near this level in nearby cores (Beach et al., 2009) shows that this was already an agricultural landscape in the Middle Preclassic.

In the second zone, later in the Preclassic, wetlands and disturbance taxa expanded as the Chan Cahal population rose. *Typha* and *Nympaea* as well as small and large charcoal pulsed to near their highest levels. This zone had >9,000 small charcoal pieces at 122 cm and 695 large charcoal at 142 cm. Several potential economic trees arise in the core including the fruit tree *Chrysophyllum* (sapote), the nut tree *Brosium alicastrum* (ramón), and the incense tree *Protium sp.* (copal). Two dates in the middle of this sequence at 117 cm are c. 2300 BP, Late Preclassic. Beach et al., (2015a) hypothesized that the first wetland field construction occurred in the Late Preclassic. Although we have no direct evidence for canal or ditch building before the canal fills in starting in the Terminal Classic period, populations at Chan Cahal had neared their peak and there is strong evidence for human management of this increasingly wet environment in the Late Preclassic.

Zone 3 falls between the dates of 1940 BP at 84 cm and 744 BP at 41 cm, which bracket this zone from the Late Preclassic through Post Classic periods. *Zea mays* shows up for the first time in this zone at 74 cm in the same zone as the highest amounts of charcoal, grass pollen, and pollen from fruit, incense, and nut trees. This corresponds to the second spike of large and small charcoal. By 66 cm, *Zea mays* reached 4.3% of the pollen, which is probably very close to the Terminal Classic Period, when the canals started to fill with sediment.

Above 66 cm, *Zea* and aquatic species vanish but disturbance species remain with what is the third spike of charcoal, dated around 1200 CE. Interestingly, Nympaea and Typha are no longer in the record above 66 cm but fern spores and charcoal reach their peak during and after the *Zea mays* presence. Schneider and Geoghegan (2006) and later Schneider and Fernando (2010) found that bracken fern (*Pteridium aquilinum*) commonly invaded and inhibited succession in intensively burned environments in the Yucatán. Because these are dates from aggrading soils, this whole zone may correspond to a mix of the Terminal to Postclassic, which corresponds to the canal's last uses, abandonment and filling near here, but possible continued or reuse of the region (Beach et al., 2015a)

Beach et al., (2015a) previously discussed a vibracore in the Chan Cahal canals, which came from a 3-meter wide canal intersection between fields close to the T1 Neuendorf wetland field. We review and expand on the stratigraphy and chronology of this core here to provide insight into the stratigraphy of the Neuendorf fields. The Chan Cahal canal core exposed the same paleosol that we have defined elsewhere in the Chan Cahal and Neuendorf trenches. The top of the core sequence is rich in organic matter and peaty clay, with a layer of peat at 62 cm that has a modern date. We interpret this as canal fill down to about 90 cm, mixed from deforestation and piling up slash after clearance in the late 1950s. Thus, the sediment from 90 cm to the surface is canal fill that accumulated sometime after canal digging removed the upper 90 cm of soil. Below the canal sequence, we recorded a truncated soil, which was an organic, gypsic clay (Cgy horizon) from 90 to 130 cm, with an AMS age of 1860 +/− 30 BP at 103 cm. Between 130 to 175 cm in the core was a zone of reduced gray clay (10YR 5/1 and 8/1) with a few 5mm thick 10YR2/2 brown laminae. A date from 140 cm in this zone was 1950 +/- 30 BP. Below this was the well-developed paleosol from175 to 200+ cm with an AMS age of 2550 +/- 30 BP (or 2 σ Cal BC 800-549). We again classify this widespread buried soil from the Middle Preclassic as a paleosol, the Ekluum soil buried by the aggradation of gypsum rich sand and clay above it due to floods and a rising water table (Beach et al., 2015a).

4.4.3 Excavations and Proxies at Sierra de Agua.

Sierra de Agua was difficult to reach via a rough road with a short window of access, but we excavated two units, one in a natural wetland and one in a wetland field (Figure 4.4). The region includes scattered karst ridges with Maya mounds and a flat *bajo* with a perennial water flow and a water table at a depth of 2 m during the end of the dry season. Sierra de Agua unit 1 was a 1.5 by 1.5 m excavation into a natural wetland soil without defined canals or raised fields in the near vicinity. This soil had an O horizon from 0- 7 cm with many roots and leaf litter (Table 2). Below this from 7-20 cm was a thick, clay-textured A horizon (2.5 Y 2/0) with high soil organic matter (SOM) and granular or subangular, blocky structure (sbk). Below this from 20-40 cm was an ACgy horizon, mottled gray and black (10 YR 6/8 + 7/8 and 2.5Y 3/0) with low SOM, sbk structure, and clay texture. The ACgy transitions to a full Cgy horizon by 40 cm and continues down to 120 cm. This zone has massive clay mottled with orange and gray and did not react with HCl when tested, indicating non-effervescence and low carbonates. The Cgy2 horizon from 120 to 150 cm is a light tan clay (10YR 8/1) and green (5G 6/1) that had strong effervescence to HCl. Throughout this portion of the profile there were well defined gypsum crystals as well as powdery gypsum masses. At 105 cm the soil profile becomes more sandy clay with decomposing organics and no HCl effervescence. At 120 cm below the surface, the clay becomes reduced and greenish (5G 6/1) again with no HCl effervescence. At 150 cm and below we reached decomposing limestone above bedrock. This final layer produced a strong HCl effervescence. There was evidence of bioturbation and disturbance in the form of krotavinas throughout the profile, and we found no samples for radiocarbon within this sequence.

Unit 2 was a 1.5 by 1.5 m excavation in the middle of a wetland field surrounded by running canals. This unit exposed a 2 m profile. The surface horizon was an 11 cm thick, very dark brown (10YR 2/2) Oe horizon with many roots (Table 2). Below this was a 11-23 cm thick, light gray (10YR7/1) Cy horizon, mottled with many white gypsum masses and 10 % orange mottles (10YR 6/8) along roots. The Cy horizon had a pH of 7.1, low SOM of 2.4 percent, and had wavy transitions above to the O and below to the ACgy horizon. The ACgy horizon ranged from 23 to 50 cm, had a pH of 6.7, and an SOM of nearly 6 percent. This horizon had visible gypsum and SiCl texture. From 50 to 70 cm was an Oa horizon with a pH of 4.7 (very strongly acidic) with more organic matter (SOM content of more than 20 percent) and charcoal visible in the field. At 55cm, charcoal from this layer produced an AMS age of 1304 +/- 30 BP. From 70 to 120 cm was the ACg2 horizon, a dark gray clay (5Y 4/1) with lower SOM (4-5%) and the pH was 6.2-6.8 (neutral to slightly acidic). Between 120-140 cm below the surface was a layer of rounded and flattened boulder to cobble sized (20-40 cm diameter) limestone and chert clasts, as well as many mixed ceramics that were too eroded to type confidently. This human built layer lay directly on a sterile Oab/ Ab horizon from 140 to 170 cm with 21 to 16.7 % SOM. This black (5Y 2.5/1), organic clay loam and loam had a pH range from 4.7 to 6.4 (very strongly acidic to neutral). Below 170 cm was the 2Cg horizon, a gray, pH neutral clay with less than 2 % SOM. At 140 cm in the Oab horizon, charred organics produced an age of 3107 +/- 38 BP, and at 170 cm near the boundary of the Ab horizon, charred organics produced an age of 3349 +/- 33 BP, which would be Maya Early Preclassic.

Each horizon in SDA2 produced good pollen preservation and particulate charcoal. The stratigraphy of the profile coupled with the paleoenvironmental proxy data show dramatic changes through three discrete zones (Figure 4.4). From the bottom up, the first zone is the buried soil of the wetland that preceded the wetland field. The Oe horizon ranged from 140 cm to 150 cm, which lay atop the Ab horizon from 140-170 cm. Below the Ab lay a gray Cg horizon from 170 cm to the bottom of the unit. The sample at 170 cm had mediocre preservation at the bottom of the Ab, but produced a strong tropical forest wetland signal with high *Crysophila stauracantha* (fan palms), *Sapotaceae* (sapote), *Cyperaceae* (sedges), ferns, and Asteraceae pollen and phytoliths. At 145 cm in the Oeb horizon the pollen changed as preservation increased. Evidence for anthropogenic disturbance increased with large and small charcoal rising by more than 5 times, and fern spores and Pinaceae and Asteraceae pollen increasing and tropical forest species declining. Two radiocarbon dates, one at 170cm and the other at 149 cm, place this zone about 3,000 years ago (3349 +/- 33 BP and 3107 +/- 38 BP, respectively.), which is just a few hundred years before the general start date of the Middle Preclassic period (2950–2350 BP). The soil at the bottom of this layer has a neutral pH of 7, but becomes more acidic in the buried peat with more than 20 % SOM to a pH of 4.7 directly below the rock layer. Phosphorous is relatively stable around 4 mg/kg within this level. The texture of this entire portion of the profile is over 50% clay. The $\delta^{13}C$ value of the lower Ab horizon at 170 cm has the signature of tropical forest, with a value of -27.45‰, but this rises to -19.45‰ at 150 cm near the increase in Poaceae pollen, significantly enriched in $\delta^{13}C$ close to the disturbance zone above it.

Zone two is a disturbance zone that begins around 50 cm and continues to about 147 cm. We interpret this as the ancient Maya raised field section of the excavation built of a rounded stone base from 125 to 147 cm, with plentiful undiagnostic ceramics, and clay soils up to 50 cm. The stone base is comprised of river boulder and cobble sized rounded stones built as a multilevel stratum. The pollen sample from above the cobble floor at 105-110 cm has excellent preservation and high pollen diversity. Here tropical forest pollen taxa decline, while, Asteraceae pollen, which we interpret as human disturbance taxa, increase to over 50% of the pollen. Poaceae (grass) pollen, another disturbance taxa, also increases in this zone. Some fern types rapidly decline here while other types slowly decline. There is a slight increase in some aquatic species such as water lily (*Nyphaeceae*) and cattails (*Typha*). Most notable within this assemblage is the presence of two major Maya cultigens, maize and Manioc pollen. Manioc (*Manihot esculentum*) is infrequent in Maya botanical records with few confirmed from pollen cores and from macrobotanicals in middens and some volcanic strata (Jones, 1991; Lentz et al., 2002, 2014; Sheets et al., 2011, 2012). Microcharcoal levels also peak within this level with absolute counts at over 200,000 pieces of charcoal that range from 10-80µm and over 20,000 pieces that are > 80µm. In this zone, pH becomes more neutral again with values that range from 6.7 to 7.4 probably due to the influence of limestone boulders. Phosphorous fluctuates between 4-6 mg/kg within this zone. The $\delta^{13}C$ value ranges from -22.2‰ to -20.9‰, which is high in $\delta^{13}C$ of C_4 taxa like the *Zea* and other tropical Poaceae that increase in this zone. The next pollen sample from 55 cm is the top of the ancient Maya field and represents a transition from the Maya field to aggradation by slow wetland deposition after field abandonment in the Oa and Ab/Cgy horizons. Charcoal and ferns are still high and *Pinus* increases but more tropical forest species return as asters and grasses decline. Although plentiful in disturbance indicators, there are no Maya cultigens within this top zone. An AMS data places the 55cm layer at 1,304 +/- 35 years BP, squarely in the Late Classic. The soils at 55cm are more acidic (with a pH of 4.7), but in general are neutral throughout the rest of the zone with an average pH of 6.9. At 55cm, phosphorous increases to 6.4 mg/kg within the soil but declines slightly to 5.6 mg/kg towards the top of the sequence.

Zone 3 above 50 cm includes the Oa to ACgy horizons Here we observe the return of tropical forest pollen and a decline in grass species and change in ferns. Aquatic species disappear from the pollen record towards the top of the unit, and microscopic charcoal of all sizes declines. The top portions of this zone are silty clay loam in texture. These upper zones return to more negative $\delta^{13}C$ values of -28.37‰ and -27.22‰, which corresponds to the rise in tropical tree species again.

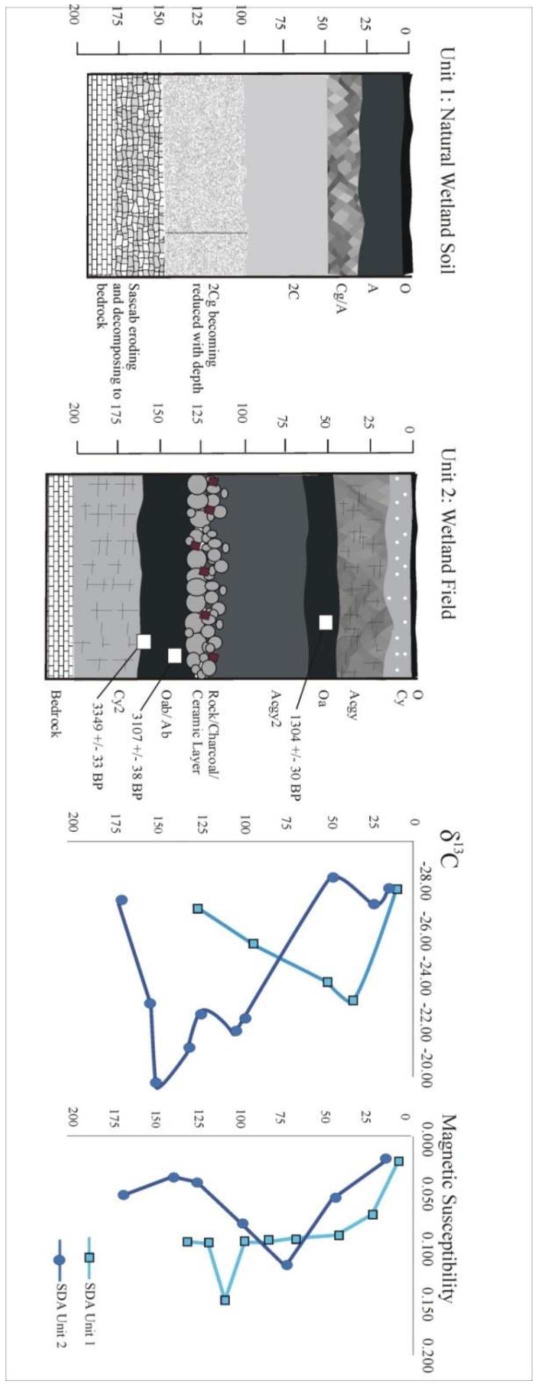

Figure 4.4. Sierra de Agua trench stratigraphy, magnetics, and carbon isotopes.

4.5. Discussion:

The Sierra de Agua pollen core from the 1990s came from a small body of water adjacent to wetland fields and canals (Dunning et al., 2003). The core was 60 cm long and one radiocarbon age at 50-55 cm was 1240 +/- 40 BP, the Maya Late Classic. The cultigens, again maize and Manioc pollen, in this older core came from 55 to 45 cm and aquatic, herb, and cultigen taxa dominated from 60 to 30 cm, above which tropical forest species dominated. This was a simple sequence indicating Maya Late Classic disturbance species and tropical forest wetland recovery dominated by mangroves.

The pollen results we present here come from a buried soil sequence in a raised field system. This is a challenging sequence to date, which can only provide broad zones of chronology (Figure 4.7). We hypothesize that the zone from the Ab horizon from 150 cm to the bottom was the pre-disturbance zone. Evidence for disturbance starts near the top of the Ab horizon where the $\delta^{13}C$ value rises from -27.5 at 175 cm to -23 ‰ at 155 cm and charcoal increases five-fold from 170 to 150 cm. An AMS date at 147 cm is 3107 +/- 38 BP. This is only one AMS age, though the lower date of 3349 +/- 33 BP, just 30 cm below, is quite close to this age and the ceramics from this rock layer are undiagnostic. The major anthropogenic layer occurs from the rock layer to 55 cm, where we report the *Zea* and *Manihot* pollen at 105-110 cm and elevated $\delta^{13}C$ values from -19.5 to -22.6‰. The date at 55cm of 1,304 +/- 35 years BP is nearly the same as the 50-55 cm date from 1990s where Dunning et al., (2003) reported *Zea* and *Manihot* pollen. Our other excavation, Unit 1, was in a wetland away from field and canals and had only $\delta^{13}C$ values to assess anthropogenic change, recording an increase of -27.9 to -23.1‰ from the surface to 55 cm and back down to -27.2 at 125 cm. We hypothesize that both units record the Maya Classic period and its changeover from tropical forest to more grasses and cultigens and back to tropical forest again. The only cultigen evidence and disturbance charcoal in the Maya raised field falls from 150 to 50 cm, and all anthropogenic disturbance disappears above this, as in the upper 30 cm of the earlier core (Dunning et al., 2003).

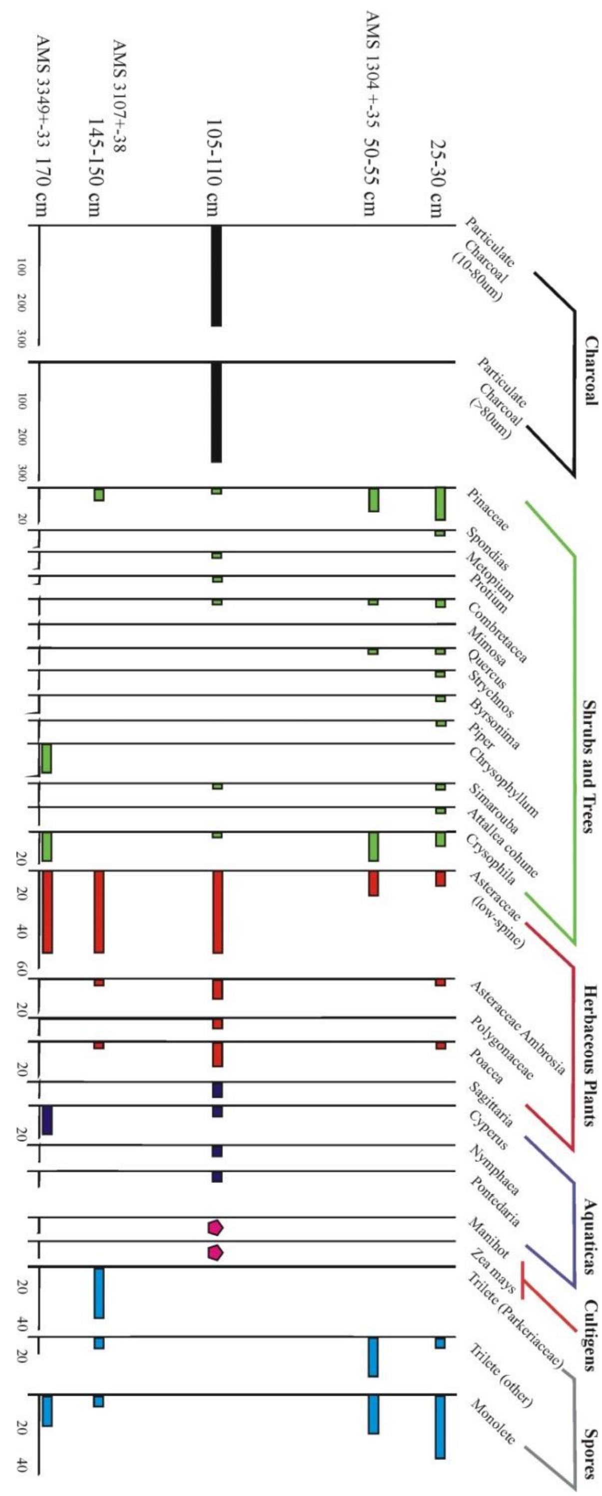

Figure 4.5. Sierra de Agua pollen.

Beach et al., (2009) interpreted similar evidence at Chan Cahal to indicate ancient Maya adaptation to water table rise. At Chan Cahal, during or after the terrestrial Ab horizon became inundated and created an Oab horizon, the Maya built canals and raised fields in the Late Preclassic and Classic Period. The pattern is similar at Sierra de Agua because the Ab horizon is topped by an Oab horizon, but at Sierra de Agua, above the Oab horizon the raised field has more complicated architecture. Here the Maya built a 20 cm rounded stone and ceramic base to the field and piled clay soils above this (Figure 8). We hypothesize the ancient Maya raised the field with the cobble layer topped by the soils to maintain drainage from the surrounding canals. The main growing surface from 147 to 100 and continuing up to 50 cm had the zone with the cultigens, charcoal, aquatic pollen, and the transition from elevated up to normal $\delta^{13}C$ values was the planting surface. This surface aggraded over time with debris from the canals indicated by the aquatic pollen and occasional burning indicated by charred phytoliths and charcoal. The dates for this sequence fall sometime between 3000 years BP at 149 cm and 1300 years BP at 55 cm based on the AMS sequence, but the other date from Dunning et al., (2003) at 50 cm in the midst of their cultigen data is virtually the same as our date at 55 cm. Since all evidence for ancient Maya disturbance lies above the Early Preclassic age at 149 cm, we hypothesize that the wetland field was part of a wider Maya Classic agricultural complex, though there may have been earlier Maya agriculture based on the high $\delta^{13}C$ value of -20.9 ‰ at 140 cm level, the cultigen pollen at 105 cm, midway between the Early Preclassic age at 149 cm and the Late Classic date at 55 cm.

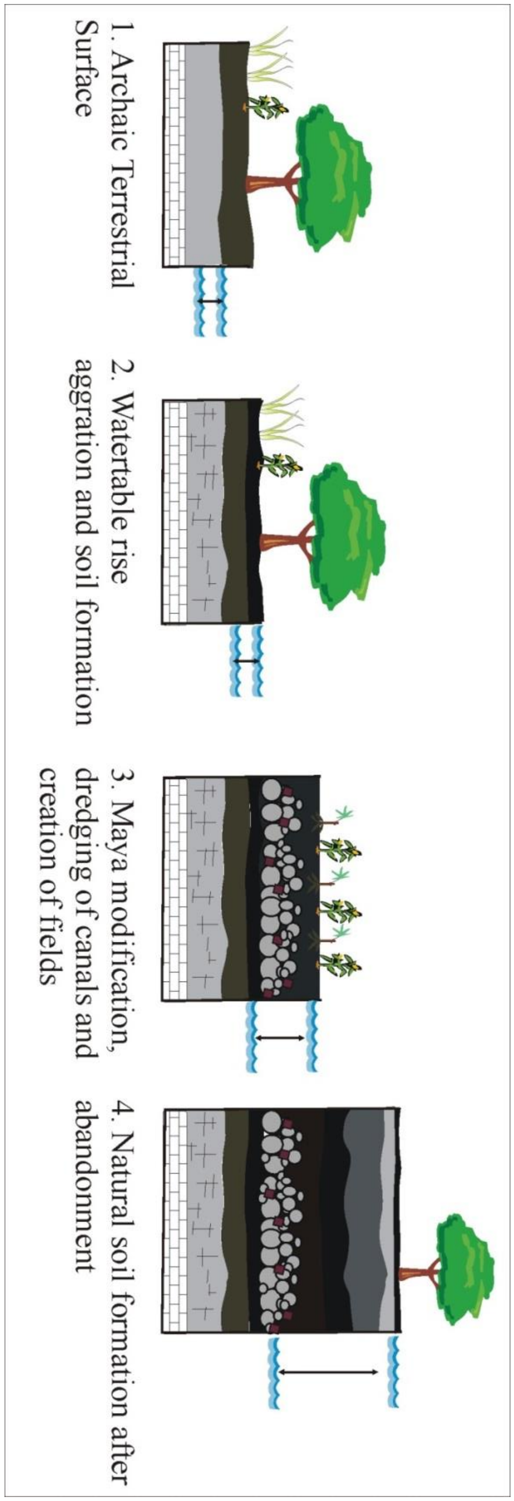

Figure 4.6. Sierra de Agua formation model.

All of the results presented show clear evidence of anthropogenic activity and large-scale environmental manipulation sometime between the Preclassic and into the Classic throughout the region, with declines in activity at the end of the Classic with no detectable reoccupation in the Postclassic. We correlate the higher magnetic susceptibility readings within the paleosols in each of these sequences to stable surfaces that accumulated ferromagnetic deposition from allochthnous volcanic and Saharan sources (Luzzadder-Beach and Beach, 2009).

This study, when considered alongside previous investigations of wetlands throughout these watersheds, demonstrates that there was extensive modification and intensive resource extraction in these wetland systems at a regional scale over at least 40 km. This provides us with a regional scale example of the lasting impression anthropogenic activity has on wetland soil sequences in the Neotropics. This information builds on our ongoing understanding of the expanding spatial scale that the ancient indigenous people of this region managed and modified their environments to extract resources and cultivate. Moreover, the timing that these soil sequences provide demonstrates the links between urban expansion and different methods of agriculture within both the Three Rivers Region and the New River watershed.

All of the results presented show clear evidence of anthropogenic activity and large-scale environmental manipulation sometime between the Early Preclassic and into the Classic throughout the region, with declines in activity at the end of the Classic and no detectable reoccupation in the Postclassic. Based on the Sierra de Agua unit 1, today a wetland soil with no visible modern or ancient disturbance, the Sierra de Agua unit 2, and that in Baker (2003) and Dunning et al., (2003), we deduce that ancient Maya modification and resource extraction in these wetland systems occurred at a regional scale. This provides us with a regional scale example of the lasting impression anthropogenic activity has on wetland soil sequences in the Neotropics. This information builds on our ongoing understanding of the expanding spatial scale that the ancient indigenous people of this region managed and modified their environments to extract resources and cultivate. Moreover, the timing that these soil sequences provide demonstrates the links between urban expansion and different methods of agriculture within both the Three Rivers Region and the New River watershed.

A noteworthy aspect of the Sierra de Agua pits is the presence of the Maya cultigen manioc (*Manihot esculentum*) in both past and present studies. This type of pollen is rare from the Maya agricultural record. Pollen grains of manioc were recovered from the persistent site of Colha (also within the New River watershed) in the 1990s by J. Jones, which was the first instance of this crop within the Maya Lowlands. Fields of preserved manioc tubers were recovered from the highland Maya site of Ceren (Sheets et al., 2011, 2012), which demonstrates the importance of this crop at least at some points within Maya agricultural history.

Soil pits and proxy data at Sierra de Agua present a new model for wetland development and modification that differ from our previous models in the Chan Cahal system. Here, we interpret a rising water table after 3300 BP followed by Maya raised field building that is more similar to the *chinampas* model put forward originally by Coe (1964). We interpret a similar raised field building strategy in which a basal layer of cobbles was placed for stabilization and drainage, with thick layers of sediment placed on top of this basal layer for agricultural purposes (Figure 4.6).

4.6. Regional Synthesis and Comparison

Our continued excavations from the well-studied Chan Cahal fields to the greater region provides us with a better understanding of the wetland system as a larger geographic region that is reasonably connected hydrologically and ecologically through both time and space during Maya occupation. Our new excavations and cores across the wetlands that makes up the Chan Cahal/Sayap Ha/Neuendorf settlement zone has produced results that generally conform with our models for wetland genesis and soil depositional patterns. Wetlands adjacent to the Rio Bravo escarpment were heavily modified during the Maya Preclassic and Classic, and peats and gypsum built up over time above a stable Archaic paleosol that generally dates to a similar time period across the landscape. This demonstrates the extent of anthropogenic modification and that the ancient Maya were active geomorphic agents for many millennia. The new trenches in the Neuendorf alluvial fan and the adjacent wetland field demonstrate that 180 to 200 cm of sediment aggraded above the Middle Preclassic paleosols. At the alluvial fan, erosion linked to upland erosion was the main culprit for the 180 cm of deposition but some of the 200 cm of aggradation in the wetland field came from Maya canal cutting and field filling and from gypsum deposition (Luzzadder-Beach and Beach, 2009).

We must always consider the role of other environmental changes like recurrent droughts such as those of the Late Preclassic and Terminal and Early Postclassic and relative sea level rise (Luzzadder-Beach et al., 2016). Perhaps both of the droughts correlate with Maya wetland fields, because some evidence exists for canal origins in the Late Preclassic and much evidence exists for abandonment in the Terminal to Post Classic (Luzzadder-Beach et al., 2012). Much research also indicates many wetland field areas started off as dry farm lands in the Archaic or Preclassic and then became inundated with water table rise (Beach et al., 2015b). The wetland fields at both Sierra de Agua and Neuendorf appear to follow this same pattern with some evidence for pre-wetland agriculture and then significant evidence in pollen and carbon isotope ratios for Classic period wetland agriculture. Thus, we suggest two explanations for the canals: adaptation to drought and/ or adaptation to water table rise. In terms of drought adaptation, we have evidence that during the Late Preclassic droughts the Maya expanded into wetland agriculture and they continued to develop and expand there through the Classic period as populations and food demands rose around these regions. In terms of water table rise, the wetland fields certainly show evidence for farming before inundation and wetland farming after inundation. Both of these explanations may play out in different environments and that we will need many studies for consensus to develop.

4.7. Conclusions

The synthesis and incorporation of these new data sets into our ongoing paleoenvironmental research provides a deeper understanding of soil systems and human-environment interaction in the late Holocene, from around 3,000 years BP to the present in Sierra de Agua, and around 2,600 years BP to the present in the Chan Cahal complex. Both wetland field complexes provide us with new insight into past geomorphic change and anthropogenic manipulation of environments during times of relative climatic and societal stability, as well as times of environmental stress or change. These new case studies further demonstrate the remarkable control that the ancient Maya had over their landscape.

Both of these watersheds are similar in regards to morphology and in regards to past use. Modification strategies and temporal scales, however, differ at these sites, and thus a regional approach with site by site considerations is a valuable aspect of this kind of large scale research.

Scholars are recognizing that persistent occupation and subsistence is an integral part of Maya culture within the Lowlands. Both the Three Rivers watershed and the New River watershed contain many perennial and seasonal wetlands that have yet to be studied in regards to delineation, biogeomorphic cycling, carbon storage, and cultural heritage. The systems reviewed here through geoarchaeological and geomorphological lenses represent only a microcosm of wetlands and wetland fields in the Neotropics. Each of these systems is unique of course but they do show similar patterns of crops, chronology, field and canal patterns, and human adaption to water inundation over a 40 km distant area. Going forward, we will need to test our hypotheses about the connections of wetland fields to drought and water table rise and myriad other factors.

Chapter 5: Wetland Paleoecology at the Edge of the Birds of Paradise[3]

5.1. Introduction

Given the outsized importance of wetland environments both in biodiversity and ecosystem services, there are relatively few studies that have focused on tropical wetland geomorphology. Through geoarchaeological research, our global knowledge of past and present wetland geomorphology has expanded, especially in Amazonia (Rodrigues et al., 2015; 2016), throughout Asia (Penny, 2006; Rosen et al., 2015; Rosen et al., 2017; Liu et al., 2017), and within the Maya Lowlands (Beach et al., 2015a; Dunning et al., 2017), where impacts on geomorphology were pervasive. The use of these two disciplines to explore complex environments such as wetlands is a methodology explored, most notably, through the varied works of Karl Butzer, (1982; 2007; 2012). The theoretical framework Butzer applied to adjacent regions (1997; 2008) provides ongoing analysis with the geomorphological framework by which we can better interpret the complex and long lasting relationship past societies had with their environments.

Increasingly, we understand that Maya civilization of Central America has a complex and long lasting relationship with low-lying wetland environments. Such wetland agricultural zones are a widespread and significant component of the landscape throughout the greater cultural and geographic area known as the Maya Lowlands. Maya

[3] An edited and expanded Chapter 5 is currently (as of August 2018) under review in the journal *Geomorphology* as part of a special issue entitled **Human Impacts on Geomorphic Systems and the Legacy Karl W. Butzer**. I am the primary author and primary data analyst for this publication. Coauthors and their roles on this publication are as follows: Timothy Beach and Sheryl-Luzzadder-Beach, who helped me implement the fieldwork design for the 2014 season and are the PIs for funding sources, lab facilities and soil permits. In addition Timothy Beach provided edits for writing and analyses. Duncan Cook served as an editor for methodology, and provided analysis for magnetic susceptibility. Gerald Islebe and Manuel Palacios-Fest served as pollen and microfossil consultants, respectively and produced these datasets within their laboratory facilities. Colin Doyle and Sara Eshleman served as field assistants and secondary data analysts for the publication. Fred Valdez and Tom Guderjan serve as PIs for archaeological permits and gave minor edits.

civilization used and altered several types of seasonally and perennially inundated landscapes for a variety of agricultural purposes from 4000 years BP to at least 1050 years BP. This use spans much of the prehispanic Maya cultural periods, from the Archaic to the Postclassic (Beach et al., 2009). In this paper, we present a new multiproxy sediment core record from a wetland swamp that lies between an ancient Maya village and a large network of ancient canals and fields in northwest Belize to understand geomorphic evolution of the wetland from natural and anthropogenic factors.

There are still only a few geomorphological and geoarchaeological investigations of ancient Maya managed wetlands within the Maya Lowlands (Siemens, 1972; Turner,1983; Pope and Dahlin,1989; Jacob 1995; Pohl et al., 1996; Fedick et al., 2000; Berry and McAnany, 2007; Beach et al., 2009; Luzzadder-Beach et al., 2012; Beach et al., 2015a, 2015b). One factor for wetland formation is the role of climate and climate change, and there is a growing body of paleoclimate records for the late Pleistocene that address long-term climate trends and drought cycles in the Maya Lowlands (Hodell et al., 2008; Medina-Elizalde et al., 2010 and 2016; Douglas et al., 2015, Beach et al., 2016). In northern Belize, Pohl et al., (1996) argued for Maya wetland fields and canals as adaptation to water table rise induced by sea level rise in the Archaic and Preclassic, though Berry and McAnany (2007) argued from their studies at Kaxob, Belize for Preclassic to Late Classic use of wetland fields. Beach et al., (2015) working 40 km south near Blue Creek indicated wetland fields developed as adaptation to water table rise as early as the Late Preclassic, Classic period expansion, Terminal Classic diminution, but some activity in the Post Classic continued perhaps as reoccupations. One motivation for this research is how widespread drying affected Maya societal transition during several periods of Maya history. So far, these studies have provided evidence that societal transformation and urban decline within Central America were both spatially and temporally complex.

Further, there are still relatively few local paleoecological proxy studies that focus on human-wetland interactions (Beach et al., 2015a). Paleoenvironmental studies of ancient human-wetland interaction can help us understand how Maya populations used and modified lowland environments, and possibly enhance our knowledge of human resilience during times of long-term regional drought. With this, we can tease out wetland formation factors, both natural and anthropogenic, within the region and assess the agricultural value of wetlands within the prehispanic Maya Lowlands.

The archaeological site Akab Muclil is ancient village that lies between the larger ancient cities of Blue Creek and Gran Cacao (Figure. 1). Here, Maya occupation and construction events continued from at least the Early Classic (AD 250-600) through at least the beginning of the Postclassic (AD 950-1500). Occupation at Akab Muclil thus persists after the florescence of the two main regional urban centers of La Milpa (Zaro and Houk 2012, Sagebiel 2014) and Blue Creek (Guderjan 2007). Chan Cahal and Birds of Paradise, two other wetland-focused Maya areas nearby, showed some evidence of Postclassic occupation (Beach et al., 2015a and b).

In this study, we use multiple proxies from a sediment core collected in a perennial swamp downslope of Akab Muclil to better define the geomorphic and ecological changes within the surrounding wetland. We selected this particular wetland because it is adjacent to the largest archaeological center in the midst of a significant expanse of Maya agricultural canals and fields, which could provide insight into wetland field formation and landscape modification through natural and anthropogenic geomorphic processes. With this new sediment record, we consider paleoenvironmental changes from the onset of the wetland in the Maya Early Classic (1700 to 1500 BP) to present day, focusing on land use, sedimentation, paleoecology, soil development, and anthropogenic influence on wetlands over time. We then compare the stratigraphy and development of this wetland to a broader regional understanding of wetland genesis over the past 2,000 years in the southern Maya Lowlands.

5.2. Background/Regional Setting

5.2.1. Natural Environment

The study site in northwestern Belize lies on the southeastern portion of the Yucatán Peninsula of the Maya Lowlands (Figure. 5.1). This region is both a cultural and geographical region that extends through portions of Guatemala and México (Pope and Dahlin, 1989). The region has a tropical climate that is seasonally dry with a strong wet season occurring from June through December. Two dominant factors determine wet-dry season: the annual migration of the Intertropical Convergence Zone (ITCZ) and the relative strength of the North Atlantic High (Anderson and Wahl 2014). During the dry season from December through May, the ITCZ lies south of Central America. During the wet season from June through November, the ITCZ shifts north around the Maya region, the North Atlantic High weakens and shifts north and the easterly trade winds bring moisture from warm seas and convection across the region (Lachniet and Patterson, 2009; Rushton et al., 2012; ; Bhattacharya et al., 2017).

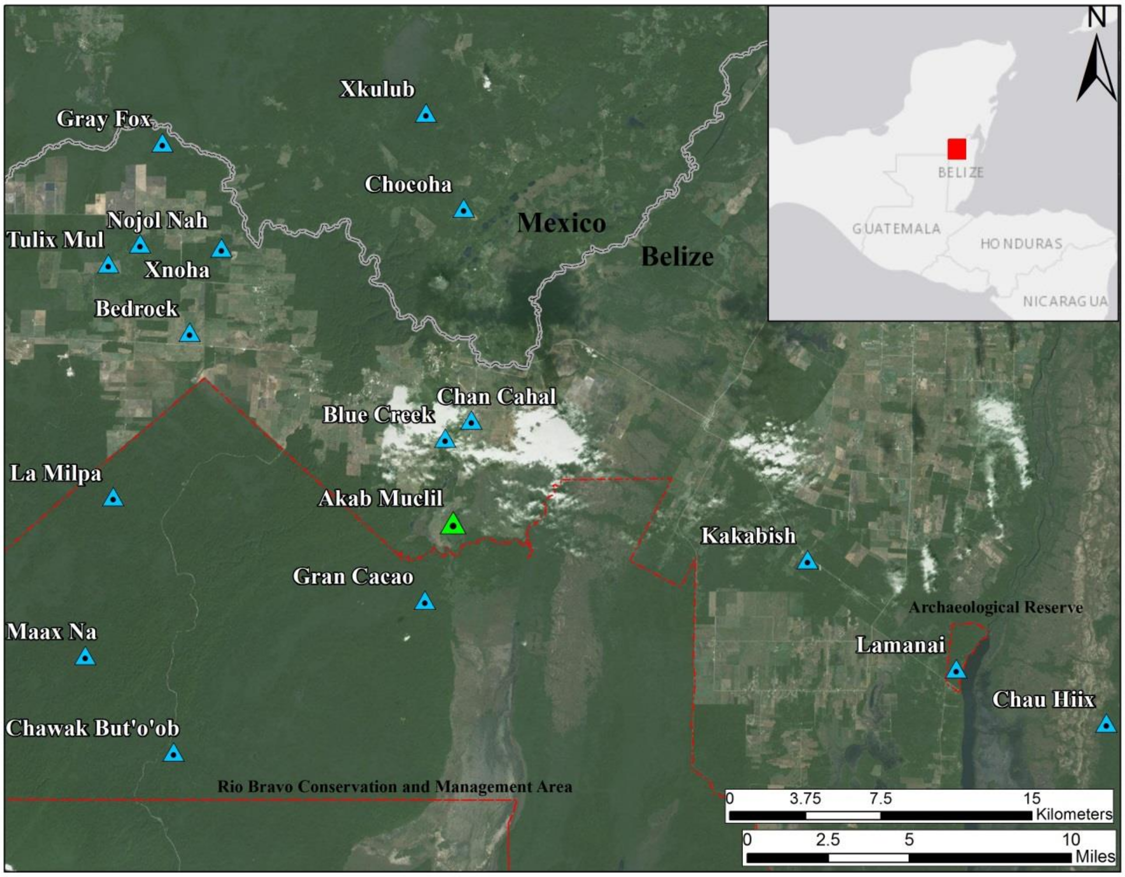

Figure 5.1. Chapter study area.

The Maya Lowlands is a karstic, carbonate, low elevation terrain, ranging from sea level to c. 300 m. Structurally, a generally parallel series of southwest to northwest trending horsts and grabens stair-step downward from the Petén region of Guatemala to the continental shelf of Belize. These create about 100-200 m of relative relief in the study region (Luzzadder-Beach et al., 2012). This karstic landscape has a variety of dissolution features such as caves, karst hills, and a variety of dissolution depressions, ranging from expansive polje-like bajos to variety of smaller sinkholes referred to regionally as rejolladas and cenotes. The coastal plain extends east of these features and into the Caribbean Sea and has a local relief of only about 10 m above sea level (masl). Deltaic progradation formed most of the coastal plain throughout much of the Cenozoic (Wright *et al*., 1959). Vegetation generally follows a topographic gradient throughout the Maya Lowlands. The riparian floodplains and the upland forests on the escarpments are dominated by broad-leaf trees and shrubs. Pine and palm savanna generally occurs in the more well-drained coastal sand plains. Closer to the coast, the vegetative communities are mangrove swamps and marshes of sedges, grasses, and cattails (Brokaw 1993, Bhattacharya et al., 2011).

Upland soils along the escarpments within the lowlands region include Rendolls, Alfisols, and Inceptisols, while the majority of depressions in the area form Histosols rich in layers of peat as well as Vertisols. All of the soils within the region form above carbonate parent material, dominantly dolomitic limestone, with some evidence of volcanic or aeolian inputs (Beach et al., 2006, 2017a, 2017b).

Wetland environments within northwestern Belize and throughout the greater Maya Lowlands serve as windows into prehistoric Maya agricultural practices and human-environment interaction. These features are commonplace and ancient indigenous groups exploited them for thousands of years in this area (Pohl et al., 1996). Wetlands occur where there is the same or more water input than output, keeping water levels near the surface. On uplifted escarpments, *bajos* and *rejolladas* are common sediment and moisture traps. Wetlands can also occur at the base of the escarpments where natural springs flow out and in areas with perched water tables. Riparian floodplains are another common type of seasonally inundated wetland, especially within the Three Rivers Region in the southern Lowlands. Finally, moving eastward across the coastal plain, are perennial wetlands of low lying marly and/or sandy marshes and swamps (Kim et al., 2002).

There are fewer paleoclimate and paleoecology studies of the central Maya Lowlands than of the northern portion of the region (Dunning et al., 2015). Some examples of large-scale paleoclimatological records from the southern Maya Lowlands come from limnological studies from Lake Petén Itza (Anselmetti et al., 2007) and Lake Salpetén (Douglas et al., 2015). The latter study, in particular, tracks wet and dry cycles that could have had an effect on prehispanic Maya agricultural patterns and landscape management. Paleoenvironmental data such as these limnological records as well as from speleothem research from the Maya Lowlands suggests particularly stressful drought cycles occurred during the Late Preclassic, the Terminal Classic, and during the Postclassic Maya periods (Dunning et al., 2012; Beach et al., 2015b). Indeed, these drought cycles continue into the historic period of the region, and understanding drought cycles and wetland dynamics within the Maya Lowlands in the past could provide insight into wetland response to drought in the present.

Several research groups are currently reconstructing moisture availability, precipitation patterns, and vegetation changes over the past few thousand years across the Maya region mostly through speleothem, lake sediment, and pollen records. Many of these records focus on late Holocene reconstructions coupled with Maya cultural transformation especially at the end of the Late Classic (Kennett et al., 2012; Lachniet et al., 2012; Medina-Elizalde et al., 2010; Medina-Elizalde and Rohling, 2012, Frappier et al., 2014). Some speleothem and lake records are able to reconstruct wet and dry cycles through the mid- Holocene and earlier in the region, most notably Hodell et al., (1995), Lachniet et al., (2004), and Pollock et al., (2016) among others. There are only a few studies that provide evidence for climate through the entire Holocene for this part of

Central America (Leyden et al., 1993; Hodell et al., 2008). This broad range of proxy datasets and resolutions provide us with a dramatically changing region from the late Pleistocene onward. In the mid-Holocene, speletothem records have suggested a slight increase in precipitation within Belize, showing less variability in rainfall when compared to later time periods the late Holocene (Pollock et al., 2016), Throughout the Yucatán peninsula and surrounding regions, the earlier portions of the Holocene are primarily dominated by arboreal tropical taxa. Many late Holocene records show drying and drought cycles in the late Holocene, which is recorded in both speleothem records and with lake cores and pollen assemblages. From, about 3500 to 1000 years BP, this trend shifts towards a non-arboreal pollen assemblage, which is often attributed to intensification of agriculture (Mueller et al., 2009; Douglas et al., 2015).

The complexity of these records and the various regional responses of Maya society throughout history does not allow for an easy answer regarding climate change, environmental response, urban abandonment, and the restructuring of cultural patterns throughout the Maya Lowlands from 950 C.E. to 1200 C.E. For example, there is extensive evidence of increased warfare and societal pressures at the end of the Maya Terminal Classic (Demarest et al., 2004; Yeager and Hodell 2008; Kennett and Beach 2013), as well as speleothem evidence indicating a precipitation decline by as much as 52 percent (Medina-Elizalde 2010, Douglas et al., 2015). Other sites within the lowlands, however, do not appear to experience the same population stress and decline at this time. Instead, these sites appear to persist or possibly strengthen politically (Masson 2000, Aimers 2007) though some connect their later declines to drought as well (Hoggarth et al., 2017). It is likely that diverse land practices, environmental interactions, regional variation, and various resource use strategies played a major, but still poorly understood, role in societal reorganization and wetland use during these key periods.

5.2.2 Cultural Environment

Most ancient and modern habitations lie on top of escarpments in this region. Akab Muclil is a Classic-Postclassic hinterland village that lies on a 30 masl high escarpment 20 m above surrounding wetlands. This ancient village lies between two larger ancient cities: Blue Creek, 4 km to the north, and Gran Cacao, 4 km to the south (Figure 5.1). Blue Creek sits on the top of the 150 masl Rio Bravo escarpment. Blue Creek had an occupation from at least the Early Middle Preclassic (~800 B.C.) to the end of the Late Classic (A.D. 600-850), and controlled at least a portion of the wetland field and canal systems below the escarpment. Gran Cacao sits on the 70 masl Booth's River escarpment. Preliminary testing at Gran Cacao suggested an occupation from at least the Late Preclassic (400 B.C-A.D. 250) to the Terminal Classic (A.D. 750-900), but it will require more intensive excavations in the future to constrain chronology. Based on their central locations, Gran Cacao and Akab Muclil must have played key roles in the wetland agriculture systems that sprawl across this part of the Rio Bravo Floodplain, most notably the area known as the Birds of Paradise fields. Previous excavations of canals and fields at Birds of Paradise demonstrated that this wetland farming system started in a flood plain tributary of the Rio Bravo around 1,500 years BP, and ancient Maya canals started to aggrade in apparent abandonment about 1000 years BP, near the end of the Terminal Classic (Luzzadder-Beach et al., 2012).

Akab Muclil lies 1,500 m east of a series of cenotes and depressions at the base of the Rio Bravo escarpment and 500 m west of a large network of ancient Maya canals and field systems (Figure 5.2). Akab Muclil also stands out because it is one of the few with

Postclassic occupations. Some of the other significant sites that did have continuous occupation from the Classic period through Spanish contact were in the Petén Lakes area (Nixtun-Ch'ich', Tayasal, Quexil, Ixlú, and Zacpetén) and in the Southern Lowlands (Schwarz 2009, Meissner and Rice 2015). Lamanai is an iconic example of relative stability and persistence from the Early Middle Preclassic through Colonial times (Graham 2000, 2004). Many other ancient centers experienced abandonment in the Terminal Classic and reoccupation during portions of the Postclassic, such as the site of Baking Pot (Hoggarth et al., 2014). Thus, urban centers and small settlement zones throughout the Postclassic were diverse spatially. Little is known about the relationship that the Terminal Classic through Postclassic Maya had with their environment, especially in regards to resource extraction, subsistence strategies, and widespread agricultural efforts. Indeed, research on highland and lowland Maya urbanism in the Postclassic demonstrates that some key centers had populations in the thousands, or in the case of Mayapán, even tens of thousands (Smith 2005), which implies continued agricultural production to some extent in lowland Postclassic society.

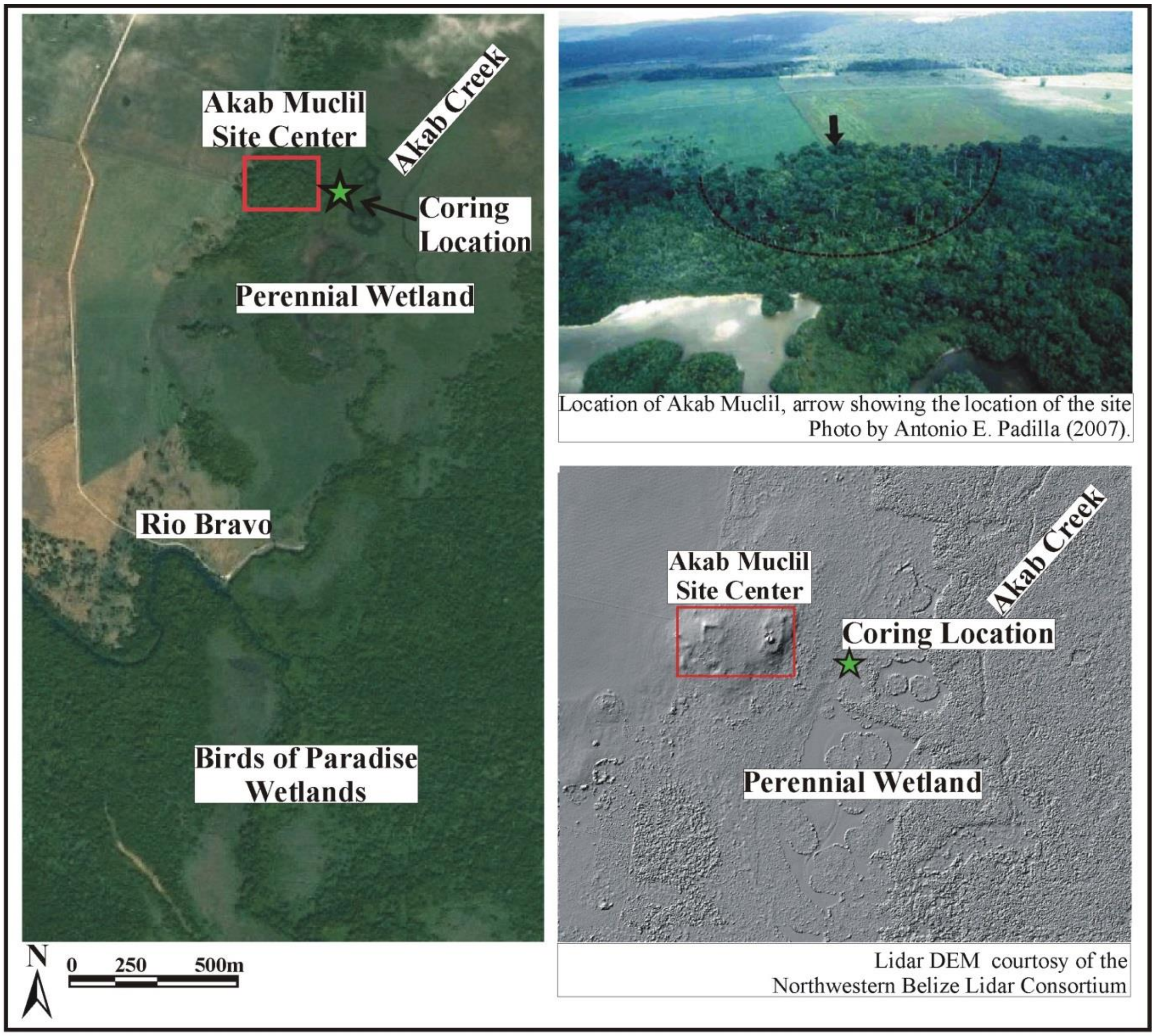

Figure 5.2. Akab Muclil study zone.

The significance of the relatively late occupation of Akab Muclil within Maya chronology is threefold. First, continuation after the generally accepted disintegration of Maya urban culture provides archaeologists with examples of human persistence during times of transition. Second, by linking these occupational sequences with geomorphic and paleoecological evidence, we can surmise what kinds of environmental changes (both natural and anthropogenic) were occurring during large-scale cultural shifts. Third, Akab Muclil's proximity to vast Classic Maya agricultural systems (Figure 2) provides us with a new lens to study Maya-wetland interaction during transitional periods from the Classic to the Postclassic. Archaeological investigations confirm that most of the larger ancient cities in Maya Lowlands experienced florescence during the Maya Classic and significant decline in the Terminal Classic (Guderjan 2007, Valdez 2007, Sullivan et al., 2008). Some of these abandoned large centers became places of pilgrimage for the Postclassic Maya, such as Colha (Masson 2000). Meanwhile, other smaller hinterland settlements in the same geographic region remained relatively resilient during the societal change of the Terminal Classic. The Maya occupied or reoccupied cities to some degree through the Postclassic, as was the case of Mayapan (Russell 2013) and Laguna de On (Masson 2000). The Maya also occupied the shores of perennial water bodies during the Historic period, such as in the case of a few Petén cities (Schwarz 2009). A variety of factors must be considered during attempts to understand the cultural transition throughout the Maya Lowlands. These factors include sociopolitical stability, as well as access to natural resources and response to environmental change.

There have been two formal archaeological excavations at this settlement, one in 2005 (Padilla 2007), and the other in 2012 (Preston and Guderjan, 2012). These excavations provide general ceramic chronologies for the site's occupation as well as information on architectural patterns and building features. Archaeological chronologies suggest occupation from the Early Classic to Early Late Classic (A.D. 250–600) and then reoccupied in the early Postclassic (ca. A.D. 900). Survey and excavation efforts beginning in 2005 revealed that the site center has two main platforms constructed on the limestone bedrock of the escarpment and at least thirteen main elite buildings. Padilla

(2007) used ceramic analysis and architectural sequences to identify Early Postclassic occupation phases at five major buildings in the site core. Structure 1 had the largest Early Postclassic construction event; here the Maya extended the main platform with new structures built on top of earlier Classic building phases. The construction at Structure 6 was entirely within the Postclassic period (Padilla 2007; Preston and Guderjan, 2012).

Recent LiDAR surveys in the summer of 2016 confirm many years of pedestrian survey around the Akab Muclil site (Figure 5.2). This group of structures is a hinterland settlement within the greater Blue Creek/Gran Cacao region at some point in prehistory. Moreover, the 2016 LiDAR survey reveals that Akab Muclil is even closer in proximity to the Birds of Paradise (BOP) Fields, than originally thought. BOP is a large-scale agricultural system of canal and field features with little evidence of lasting masonry structures. Geoarchaeological excavations of canals and fields at the Birds of Paradise date the sediments that fill the bottom of canals to the Maya Terminal Classic with evidence for some use in the Postclassic (Beach et al., 2009). This record of use parallels Akab Muclil's occupation and what little we know of of Gran Cacao's, which generally correlate with activities occurring in nearby field systems.

5.3. FIELD METHODS

Using a Livingstone piston corer, my team recovered one 2.5 meter long core from wetland sediments 100 m east of the site of Akab Muclil in May of 2014, during the height of the dry season. We collected the core in standing water (approximately 50 cm deep) in a saw-grass (*Cladium mariscus subsp. jamaicense*) and mangrove (*Rhizophora mangle L.)* dominated swamp (Figure 5.2). We also collected four short (<1 m) cores from the surrounding swamp to delineate modern wetland geomorphology, ecology, and sedimentation. We collected and analyzed the basic water chemistry of the wetland system and tested pH (8.08), Electrical Conductivity (526 mS/cm), and Oxidation-Reduction Potential (-68.8mV). We also collected water samples from the surrounding watershed, including the nearby Cacao Creek and swampland.

We extruded and subsampled the core in 1 cm increments at our laboratory facilities at the Maya Research Program. Every third sample we shipped to El Colegio de la Frontera Sur in Quintana Roo, México for pollen and microcharcoal anaylsis. We sent the remaining bulk of the core to the University of Texas at Austin, where they remain in storage at 3-4 degrees C. Manuel R. Palacios-Fest analyzed microfossils at Terra Nostra Earth Sciences Research, LLC (TNESR).

5.4. Laboratory Methods

5.4.1 AMS dating and Age Depth Modeling

We used four AMS radiocarbon determinations to date the 2.5 m sediment sequence from Akab Muclil (Table 5.1), showing that the core spans from 1675 (+/- 30) cal years BP, through the Maya Early Classic onward to the present. We modeled the sedimentation rate with the R statistical package Bacon, after Blaauw and Christen (2011).

5.4.2. Pollen and Micropaleontology

Dr. Gerald Islebe at El Colegio de La Frontera Sur in Campeche, México conducted pollen and charcoal analysis on 42 samples from 2.08m to 0.06m depth in the core. Pollen groups from tropical forest, tropical savanna, aquatics, disturbance taxa, and cultivated taxa occur throughout the core (Figure 5.3). Dr. Manuel Palacios-Fest at Terra Nostra Earth Sciences Research analyzed four micropaleontology samples at 34, 103, 152, and 212 cm within the wetland zone of the core, above the lower paleosol. He prepared sediments for microfossil investigations using routine procedures (Forester, 1988) modified by Palacios-Fest (1994). Using a low-power microscope Palacios-Fest identified macro- and microinvertebrates and algae in these samples.

Table 5.1. Akab Muclil Radiocarbon Dates.

Sample #	Depth (cm)	Material	Conventional Age (BP)	2 σ AD/BC
Akab Muclil Core				
bz14am01b1	0.1-0.2m	Plant Material	104.6 +/- 0.3 pMC	Modern
2-2016-3	0.82-0.83m	Organic Sediment	830 +/- 30 BP	Cal AD 1210 to 1275 (Cal BP 740 to 675)
2-2016-5	1.76m	Carbon	1120 +/- 30 BP	Cal AD 895 to 1020 (Cal BP 1055 to 930)
bz14am01b213	2.14-2.15m	Carbon	1690 +/- 30 BP	Cal AD 255 to 295 (Cal BP 1695 to 1655)

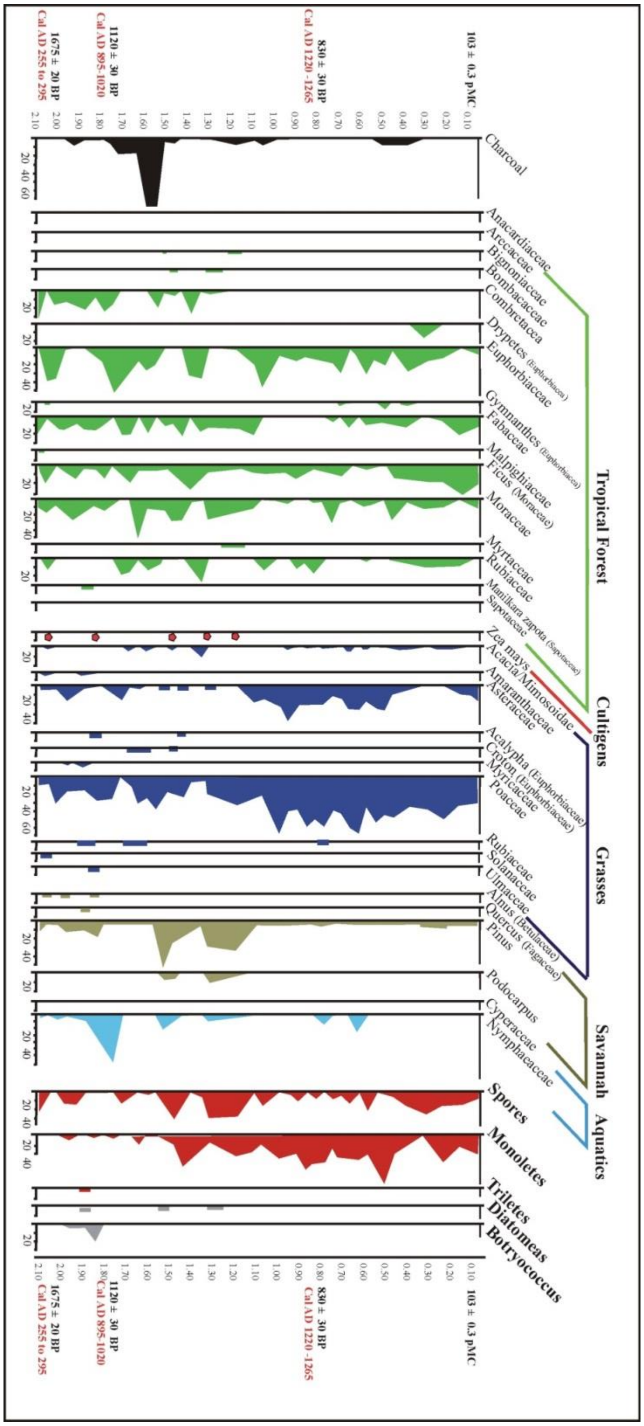

Figure 5.3. Pollen analysis of Akab Muclil core.

4.3 Loss on Ignition/Magnetics

I preformed Loss on Ignition (LOI) down-core in the Soils and Geoachaeology laboratory in the University of Texas at Austin based on the standard method by Dean (1974) and later modified by Lotter and Lemcke (2001). First, we used the 550 °C degree burn to remove all organic material from each sample. We then burned the samples at 1,000 °C to remove carbonate material from each sample.

Magnetic Susceptibility is a common method in geoarchaeological and paleoecological sequences. A soil can develop magnetic qualities due to a number of natural and anthropogenic processes, such as burning and deposition of magnetized sediments, or through biological processes and the breakdown of organic materials (Oldfield 1999). I measured the magnetic susceptibility of air-dried, disaggregated sediment samples from Akab Muclil in low (0.46) and high (4.6) magnetic using a Bartington magnetic susceptibility meter model MS2 interfaced with a 36 mm internal diameter dual-frequency sensor type MS2B following the procedure outlined in Gale and Hoare (1991). Recalibration of the MS2 meter was made between each sample and we also ran a Bartington magnetic standard through the measurement sequence to capture any instrumental drift.

4.4 Inorganic Geochemistry/XRF

Abundant studies in geoarchaeology have suggested that there is a correlation between human activities and the relative abundances of elements such as P, other trace elements, and organic compounds within soils (Proudfoot 1976; Houston et a., 1999; Terry et al., 2004; Cook et al., 2006; Dahlin et al., 2007; Wilson et al., 2008; Cook et al., 2017). P analysis has proven useful within the Maya Lowlands, because soils in this region have very low natural levels of P. When P flushes into this predominantly calcareous environment, calcium ions coupled with high soil alkalinity makes P more insoluble and buildup in soils and sediments rather than taken up in food webs (Dahlin et al., 2007).

I analyzed the wetland core specifically for phosphorous using methods detailed by Terry et al., (2004) and Dahlin et al., (2007), calculating the concentrations of phosphorous down core using the Mehlich II procedure for extractable phosphorus. I subsampled 20 samples down the length of the core and mixed 2g of material from each sample and mixed each with 20 ml of Mehlich II extraction solution. The samples were then agitated and filtered through a 15 cm filter paper. An aliquot of 1 ml of the solution was transferred to a colorimeter vial and diluted to 10 ml using deionized water. I then added a packet of PhosVer 3 Reagent to each vial and shaken for 60 seconds, and let to rest for four minutes to develop the color. I calculated each sample and a blank using a Hach DR/850 Colorimeter on the % Transmittance function. Detailed information on this method can be found in our recent studies in Beach et al., (2017).

I also analyzed the relative abundances of inorganic elements from the Akab Muclil sediments using X-ray florescence (XRF) on 20 samples down core to determine elemental concentrations by weight percent. After drying and powdering I analyzed the selected samples using an Olympus BTX profile XRF on Helium mode to better analyze light elements. In addition, I sampled nearby surface waters to determine baseline modern hydrological chemistry (pH, electrical conductivity, sulfates, chlorides) of the swamp water.

4.5. Stable Isotope Analysis.

Carbon production and storage within wetland can be reflected within their sediment sequences. Important contributors to soil C within wetlands include microbial biomass, plant detritus, and sediment inputs (Wooller et al., 2003a; 2003b; Adame et al., 2016).Additionally, human-induced vegetation shifts can drive significant differences in the isotopic signature of both terrestrial and wetland soils. Webb et al., (2004), describes how plant physiology and photosynthesis processes determine the carbon isotopic value of the plant organic matter within soil. Specifically, many trees and temperate grasses (C_3 plants) use the Calvin cycle photosynthetic pathway. Tropical grasses sedges, and central to this research, maize, (C_4 plants) use the Hatch-Slack cycle photosynthetic pathway. Scientists discovered this distinction between photosynthetic pathways by observing the large differences in $\delta^{13}C$ values of the two plant communities (Sharp 2006). The C_3 plants tend to have an average isotopic signature of -28‰ to -26‰, while C_4 plants average about -13‰ to -12‰ (Sharp 2006). Archaeologists and paleoecologists have found these plant isotopic differences to be valuable, because the isotopic composition of plants with some fractionation after a plant's death transfers to their soils (Webb et al., 2004), especially the humic substances of soil organic matter (SOM), which are the oldest and most resistant to decay. Past studies on SOM within Mesoamerica have correlated the most positive $\delta^{13}C$ values within soil sequences with maize agriculture (Webb et al., 2004, 2007; Beach et al., 2009; Burnett et al., 2011; Dunning et al., 2015).

After removing carbonates with HCL in a shaking hot water bath, I analyzed carbon isotopes every 15-20 cm down core. This entailed measuring the ratio of the isotopes ^{13}C and ^{12}C and reporting the isotope ratio as $\delta^{13}C$ values with the ‰ unit against VPDB (Vienna Pee Dee Belemnite). Generally, we can attribute an increase or shift < 3.5‰ to natural bioturbation or microbial activity (Webb et al., 2004; 2007). We, therefore, attribute a shift of 3.5 ‰ or greater $\delta^{13}C$ values within a profile to vegetation change (Balzotti et al., 2013). These results are synthesized and compared with other regional excavations and cores.

5.5. FINDINGS

The modern environment around the archaeological site of Akab Muclil is a perennial low-lying woodland swamp characterized by mangroves and sedges. The present day water chemistry is characterized by high levels of sulfur and calcium. The sediment core extruded from the swamp represents 6 distinct ecological/sedimentological zones spanning at least 1675 years (Figure 5.4).

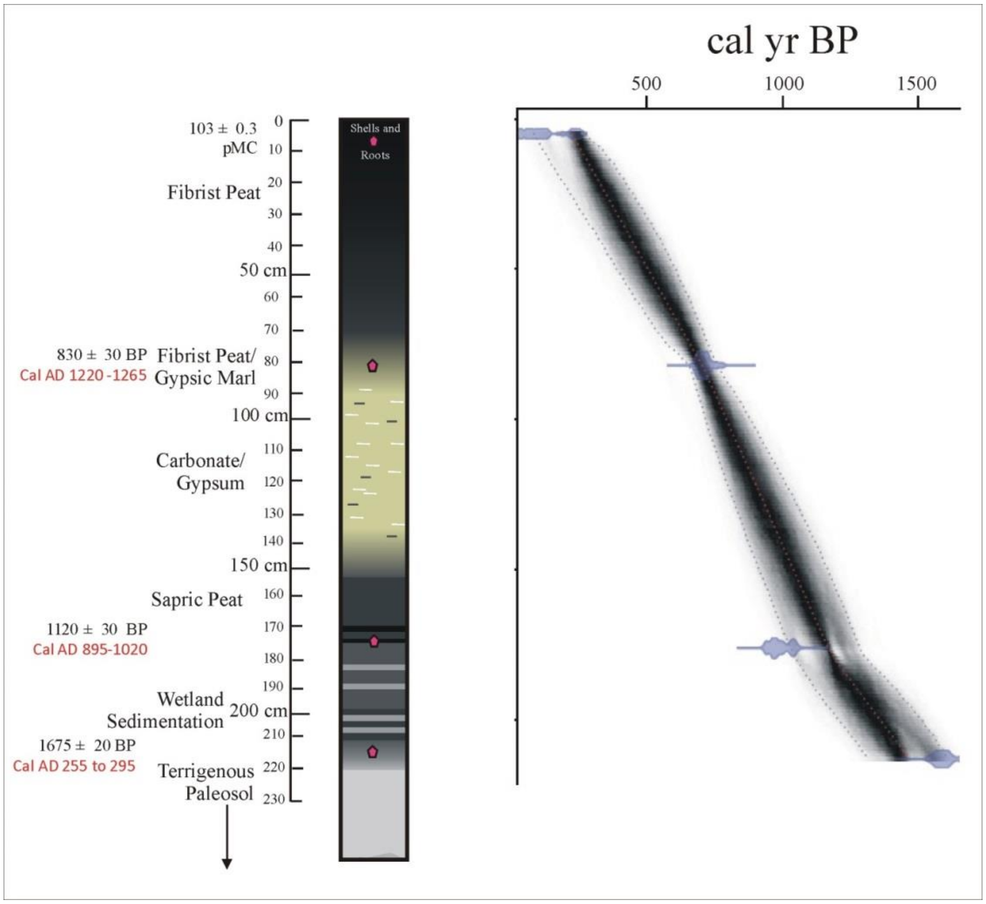

Figure 5.4. Sediment profile and Age-Depth Model.

5.5.1 Soil Description, Age-Depth Modeling

The basal portion of the core (2.60-2.20 cm) is a terrestrial soil, composed of gray (Munsell Gley 1 7/N to 5/N), massive clay with few, fine gypsum crystals. Above this (2.20-2.09m) the material transitions to dark, gray clay (Munsell Gley 1 4/N), rich in organic material and shell fragments. From 2.09 to 1.76 m there are laminated sequences with several sharp transitions from lighter to darker gray clay to lighter-colored silty sediments, which we interpret as changes in depositional energy in the environment. At 1.70 m, the soil changes to a homogeneous dark, peaty, silty clay that transitions upward into a Saprist peat (OM=64%-70%). At 1.54 m, there is a sharp transition to a light gray/dark gray marl with occasional, faint, silty clay laminations which persists until 0.88 m. Above 0.88 cm the organic rich sediment transitions into a mix of Fibrist peat and gypsic marl at 0.73 m. The zone from 0.72 m to 0.12 m is a very dark, silty clay Fibrist peat with little decomposition. The top 12 centim of the core are composed of dark, Fibrist peat, shells and roots (OM=73%). In review, this core showed a terrigenous paleosol at its base overlain by multiple depositional episodes of wetland sedimentation, peat development, and carbonate and gypsum precipitation extending until the present.

There are several ecological transitions within the wetland sequence based on both faunal and floral changes as well as shifts in the overall geochemistry in the sediment record (Figure 5.5). Both the stratigraphy of the soils and the various results from our multiproxy studies demonstrate that various environmental changes occurred throughout sedimentation from the Early Classic to the present. We divided the core into 5 distinct environmental zones discussed below (Figure 5.5).

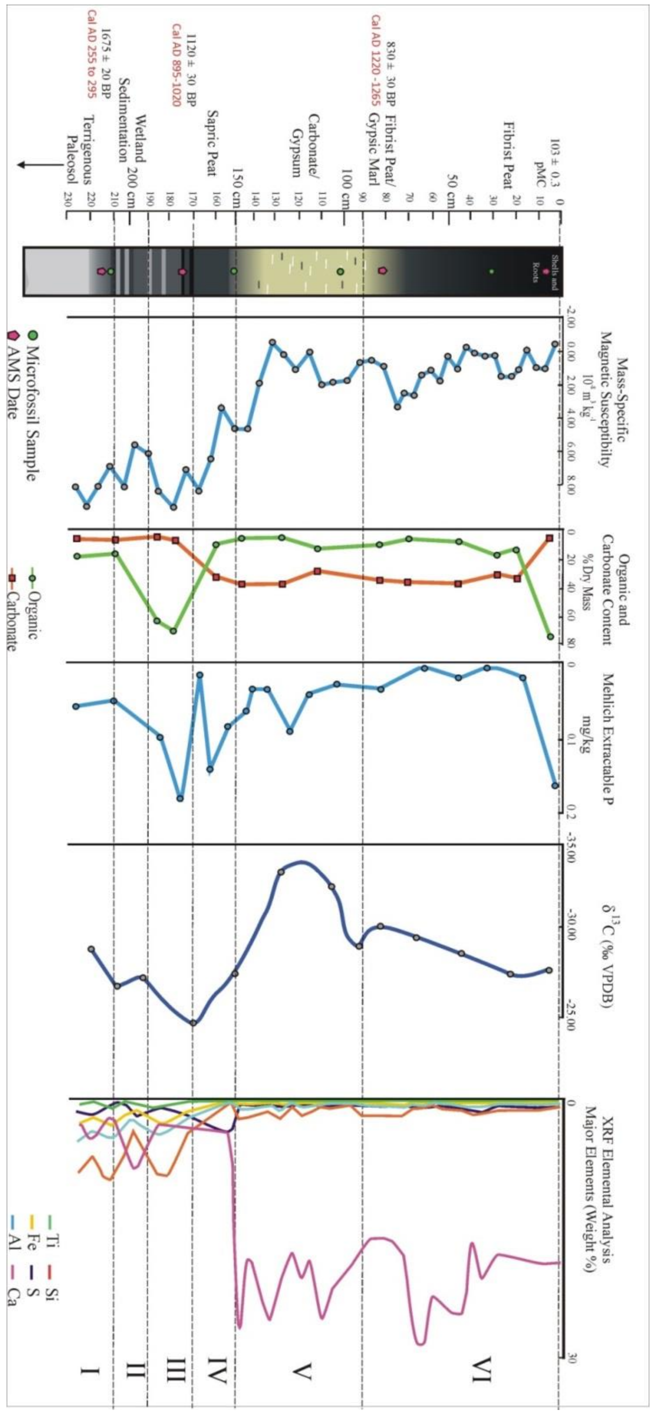

Figure 5.5. Ecological zones and geochemistry.

5.5.2 Zone 1 (2.60m-2.09m)

Zone 1 occurs from 2.6 m to 2.09 m in the core. Here, an AMS date at 2.14-2.15m places the base of the core to the Early Classic Maya occupation, at 1675+/- 30 BP (Cal 2 σ AD 255 to 295). This peaty clay had 17.8% SOM and the highest levels of magnetics as well as the highest levels of Si, Al, and Fe within the entire core sequence, which marks a dominance of clay-rich clastic soil-like material. This entire zone has low microfossil content, which suggests poor preservation in buried soil to the early stages of deposition. The upper boundary of this zone contains fragmented shell material with no complete microfossils. The preservation of pollen was good here and indicated abundant tropical forest taxa, especially *Combretaceae* and *Euphorbiaceae* (major flowering plant families). This zone represents the topsoil of the buried soil with reduced gray colored clay and an upper boundary, a dark clay rich with organic material and shell fragments, relicts of the bioturbation of top soil. Soil carbon in this zone has a $\delta^{13}C$ value of -28.65‰, again representative of representative of C_3 and forest taxa.

5.5.3. Zone 2 (2.09 to 1.90m)

Zone 2 ranges from 2.09 m to 1.90m, where the soil starts to be buried by lacustrine sedimentation. Here there are several banded deposits from dark gray clay to lighter-colored silty sediments. Magnetic susceptibilities remain relatively high in this zone as well, perhaps resulting from deposition of eroded topsoil after forest burning. *Pinus* pollen and diverse tropical forest species are present throughout Zone 2, as well as *Zea mays* pollen at ~2.05 m near the earliest levels of deposition. *Euphorbiaceae* declines in the bottom portions of Zone 2 but makes a comeback by the top portion of this zone. This sequence preserves a small amount of diatoms *(*namely *Botryococcus).* Charcoal begins to increase in Zone 2, which parallels the high phosphorous and magnetic susceptibility. The average $\delta^{13}C$ value in this zone is -26.71, a rise of ~ 2 ‰ from below that may indicate more C_4 taxa input.

5.5.4. Zone 3 (1.90-1.70m)

Zone 3 occurs from 1.90 m to 1.70 m. Pollen and sediment composition change at 1.75 m. The soil changes to a fairly homogeneous dark, peaty silty clay that transitions upward into a sapric peat with many laminations of calcareous deposition and peat layers intertwined throughout, which we interpret as cycles of stable wetland development, influxes of water and higher energy particles into the system, and authogenic carbonate ($CaCO_3$) precipitation. Here there is also a spike in aquatic taxa (Nymphaeaceae), a less obvious, but still present, increase in diatom abundances, and a slight increase in disturbance taxa such as *Poacea* and *Asteraceae*. Charcoal within the system increases towards the top of zone 3. Organic matter values are as high as 80% of the dry mass in this peat-rich zone. Phosphorus levels begin to climb within the system as well. The average $\delta^{13}C$ value in this zone is -25.71, ~ 3 ‰ higher than the terrestrial soil.

5.5.5. Zone 4 (1.70 to 1.50m)

Within Zone 4 *Zea mays* pollen continues along with aquatic pollen taxa, and an abundance of macroinvertebrate communities with the addition of a few gyrogonites of *Chara vulgaris*, the calcareous algae (Palacios-Fest, 2014). The charcoal peaks here between 1.60 to 1.50 m. Tropical forest taxa and the aquatic taxa Nymphaseceae decline within this zone, while *Pinus* pollen expands rapidly. An example of the forest taxa decline is that Combretaceae disappears completely. The highest peaks in magnetic susceptibility also occur in this section of the core. Extractable Phosphorous (P) in this zone fluctuates from high to undetectable within this zone. The $\delta^{13}C$ values at 170cm is -24.69, ~ 3 ‰ higher than the terrestrial soil

5.5.6 Zone 5 (1.50 to 0.90m)

Zone 5 occurs from 1.50 to 0.90m, and represents the most dramatic change in geochemistry within this wetland's sedimentary sequence. Clays are replaced by silty materials in this zone, made up primarily of authogenic minerals. Levels of Ca and other light elements increase dramatically here and remain dominant throughout the rest of the core, while Si, Al, and Fe and other metals as well as P all decrease in this zone. Magnetic susceptibility declines with the reduction of Fe and the increase in calcareous material. Disturbance taxa increase dramatically within this section, especially *Poaceae.* Presence of ostracods, mollusks, and calcareous algae indicate a freshwater wetland here as well. The presence of *Zea Mays* continues through this zone up until 1.20 m. At about 1 m depth, the signal for *Zea*, *Pinus*, and other savanna pollen decreases. This shift to high light elements and low metals is visible within the zone, as a sharp change from stable peats and laminations to deposits of light gray/dark gray marl, layers of Fibrist peat, and tan marls. There are some small quantities of charcoal in the system, but P and charcoal decline throughout Zone 5 and only returns at the top of the core. Here $\delta^{13}C$ shifts considerably. At the bottom of this zone the δ value is -27.85‰, but by 1.25 m the δ value is -33.82‰. At 95cm the δ value is -28.91‰, and all of these values indicate dominance of C_3 taxa. Taken together, Zone five shows ancient Maya abandonment in the collapse of economic and disturbance taxa, the lack of sediment derived from soils (metal and clays), and increased evidence of forest taxa.

5.5.7 Zone 6 (0.90 to 0m)

AMS dating at 82cm (Cal 740 to 675 BP) puts Zone 6 in the Postclassic Maya occupation and up until the modern AMS date at the top of the core sequence. What we usually interpret as disturbance taxa, especially Poacea, dominate the pollen assemblages in this upper portion of the wetland sequence, but *Pinus* pollen remains low throughout this zone and up to the surface, demonstrating the return of tropical forest taxa up to the present. The Poacae could be disturbance or wetland grasses especially *Phragmites australis*, which is a C3 plant that can change to C4 (Srivastava et. al., 2014) and is common in the current wetlands and identified from phytoliths in ancient contexts (Beach et. al., 2009). Zone 6 also has high abundances of ostracod and mollusk populations, including an extremely rare species of ostracod, *Darwinula stevensoni*, and the calcareous algae of *Chara vulgaris* is absent in this top portion of the core (Palacios-Fest 2014). Calcium remains a dominant component within the geochemistry of the wetland, with Al, Fe, and other elements remaining low. Phosphorous is relatively high at the top of the core sequence, probably from modern agriculture. Here the average δ value for carbon is -28.75‰.

5.6. DISCUSSION

Geochemistry, paleoecology, and soil characteristics suggest that Zone 1 from 2.60m-2.2m was originally terrestrial. The dark, buried soil with high magnetic susceptibility and SOM (up to 20%) demonstrates pre-perennial wetland conditions. The soil classification is likely in the Calciaquoll Great Group of USDA soil taxonomy, due to high gypsum and calcium. Within this zone, there are higher relative abundances of iron and aluminum, which suggests a stable soil. Beach et al., (in press) hypothesized that soils in the Maya Lowlands region with high amounts of iron, aluminum, and manganese relative to the more soluble elements of calcium and magnesium are relatively older soils. From 2.2 m to the laminated sediments at 2.1 cm is an O or A horizon mixed from the floodplain buried topsoil and the rise of wetland deposition. This wetland was either intentionally created for agriculture, or a natural change in hydrology within the area, but we suspect ancient Maya management because of the numerous canals and near the location. The AMS date of 1690+/- 30 BP (Cal AD 255 to 415) from the buried topsoil coincides with the Early Classic Maya occupation , the earliest occupational sequences at Akab Muclil such as an Early Classic burial crypt in the foundation of Structure 1 (Padilla, 2007).

The changes of the sediment type, as well as microecological changes in Zone 2 (2.09 m to 1.90m) point to a transition to a new wetland environment. *Zea mays* pollen at ~2.05 m suggests Classic Maya cultivation in this zone. We interpret the zone above this, from 1.90 m to 1.70 m (Zone 3) as a continuation of the wetland. Prolific ostracods, mollusks, and gastropods occur here as well. Our AMS age at 1.76 m is cal 895 to 1020 CE, which places this zone in the the Maya Late Classic to Early Postclassic. Archaeological investigations at Akab Muclil report that the site experienced population growth in the Late Classic, and archaeological faunal evidence from Late Classic excavations suggested both terrestrial and aquatic subsistence (Padilla, 2007).

Zone 4 in particular shows a relatively rapid and pervasive ecological change within the system, even while maize pollen continues to persist through these fluctuations. In Zone 4 we interpret the increase of pine and other savanna taxa as an increase in dispersal allowed by the decreased tropical forest. The charcoal and magnetic susceptibility indicate that these fire activities could be the result of land management that led to deforestation within the population booms of the Maya Late Classic period, but also could in part be a response to regional drying throughout the Maya Lowlands, which corresponds with other late Holocene records at this time (Mueller et al., 2009, Wahl et al., 2013). Extractable phosphorous (P) in this zone fluctuates from high to undetectable within this zone, which could indicate changes in Maya land use and other human inputs into the system. Previous research on Late Classic Maya occupational areas has also found P enrichment within settlement and agricultural zones. For example, the lakes and other sinks within the Petén region of Guatemala and throughout the greater Maya Lowlands experience increased P during the Maya Classic period. Many have linked this relative increase of P across the landscape during the Maya Classic with intensive agricultural land use of both wetlands and upland agricultural zones. Many studies also report relative increases in charcoal and cultigen pollen/phytoliths at this time (Beach et al., 2008; 2015a). The presence of Chara vulgaris in this zone may correlate with the increased P since research in the Everglades suggest this species increases with P (Chiang et al., 2000). The less negative $\delta^{13}C$ value of -24.69 % suggest cultivation and disturbance with greater input of C_4 taxa within this sequence.

Zone 5 bookends Zone 2, indicating Maya abandonment and reforestation. Here, shifting pollen taxa dominance such as the collapse of maize and decrease of pine along with the decline of charcoal likely indicate a return of surrounding tropical forest and de-intensification of crops. Here the geochemistry of the change from more heavy metals to dominance by Ca indicate the decline of terrestrial, overland flow soil inputs and increase in groundwater inputs, as the underlying aquifer is limestone.

Zone 6 represents the Postclassic to the present. We interpret sediments around 80cm Zone 6 to be associated with Postclassic Maya occupation (with an AMS date at 82cm that was 1210-1275 CE). Therefore, zone 6 provides a record of sediment from the time of Maya sociopolitical reorganization and a greatly retracted population. At this time, major site abandonment at Gran Cacao and Blue Creek has already occurred. The occurrence of an abundance of these diverse mollusk populations suggests deeper, fresher, and well-oxygenated waters within this zone. *Chara vulgaris* is absent in this top portion of the core, perhaps caused by lower P before it rises again in the uppermost core. The relatively high levels of phosphorous return near the top of the core, probably due to modern agricultural and livestock runoff.

Archaeological work at the site center demonstrates that population that lived at the small hinterland site of Akab Muclil reacted to regional political instability and possible drought drivers in a different manner than other larger urban centers at the end of the Maya Classic and into the Postclassic. Geomorphological and paleoecological studies such as this wetland core study complement archaeological efforts and regional climate studies by providing this local scale of human land use and wetland development.

All proxies analyzed within this core point to a shifting wetland environment around the site of Akab Muclil during the Maya Classic and into the Postclassic. This wetland sequence correlates with previous studies within the region. A previous pollen core (Beach et. al., 2009) from Laguna Verde came from about 2 km northwest of the Akab site center. This core location was about 2.5 km southwest of the Chan Cahal fields, which Blue Creek controlled during the Maya Classic period. The Laguna Verde sequence demonstrates that a similar scenario of a terrestrial paleosol buried by a wetland occurs, but much earlier, between 4840 and 4420 years BP in the Archaic (determined using AMS dating) (Beach et. al., 2009). This pollen record showed a rise and decline in cultigen species that is typical of the usual Archaic to Postclassic trend in the region, unlike the Akab Muclil core, which may indicate the continued presence of *Zea Mays* into the Postclassic. The Laguna Verde core displays transition zones similar to the chronology and use of the Chan Cahal fields, including changes in sedimentation and pollen that correspond to the Archaic to Preclassic transition, typical Classic period ecological trends, and a decline in cultigens at the end of the Classic corresponding to the decline of the political fabric at Blue Creek site core at this time.

5.7. Comparison to Upland Catenas and Two Additional Cores in the Laguna Verde Swamp

We compare our Akab core findings with soil research in upland catena sequences in archaeological sites throughout the Three Rivers Region and around hillslopes. Beach et al., (2017) conducted catena excavations on the hillslope on which Akab Muclil is located and down into the wetland. In these catena slope studies, we evaluated two 60 cm backslope profiles located near the eastern edge of the of the site center. These excavations reported Typic Haprendoll soils that indicated significant Maya disturbance. For examples, a significant 4.3 ‰ $\delta^{13}C$ shift from C_3 toward C_4 plant species at a depth of 30cm in a buried Ab horizon on the profile closest to the Akab Muclil wetland, indicated significant inputs of C_4 species lower on the archaeological site slopes near the wetland. This finding along with many others in the region demonstrate that the $\delta^{13}C$ value of paleosoil sequences dated to the Maya Classic often have significant C_4 species inputs. We compare the relative $\delta^{13}C$ values down-core to our continued catena studies around the urban center of Akab Muclil (Beach et al., 2017). In the wetland core at Akab Muklil, similarly significant shifts of $\delta^{13}C$ shift from C_3 to C_4 in the Early Classic and C_4 back to C_3 taxa in the Postclassic, suggesting a de-intensification of maize crops, though continued maize pollen at this point in the core suggests that cultivation, likely in scattered milpas, did not end at this time.

Laguna Verde is a cenote 3 km away from the Akab Muclil swamp, and has been cored 3 times in various locations over the past several years to get at paleoecology and change over time. The first core was utilized in a previous dissertation. The second core was previously discussed by our research group (Beach et al., 2009). The second core reached a depth of 148cm with a basal date of 4800-4420 years BP. Previously, Beach et al. interpreted four main zones in this core. The lowest segment was dominated by forest taxa with some possible cultigens near the base of the core, dating to this late Archaic time period. Above this, is a zone that Beach et al. interpreted as an Archaic to Late Preclassic zone, which showed a decline in arboreal taxa and rise in aquatic taxa, which again decline steadily up to the Late Preclassic. After this in the Preclassic, cultigens increase again. In the upper levels of this core, pollen analysis showed high cultigens that decline with the rise of aquatics.

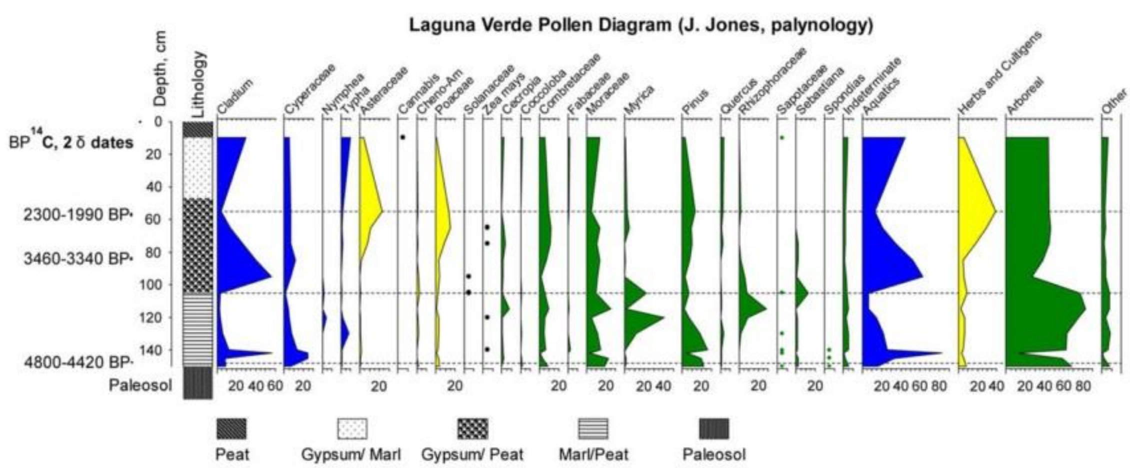

Figure 5.6. Pollen Diagram of the 2009 Laguna Verde core, analyzed and compiled by J. Jones.

In 2016, we extracted a 320cm long core from the Laguna Verde wetland, which provided a basal date of 4460 +/- 30 BP, similar to the previous core. We currently have analyzed organic matter and carbon isotopes for this new core, and will also analyze it for pollen and other microorganisms in future studies. The combined data for all of these sediment records provides complimentary data to the Akab Muclil sequence, in that it demonstrates rising aquatics in the Classic time period, and cultigens throughout the Classic as well.

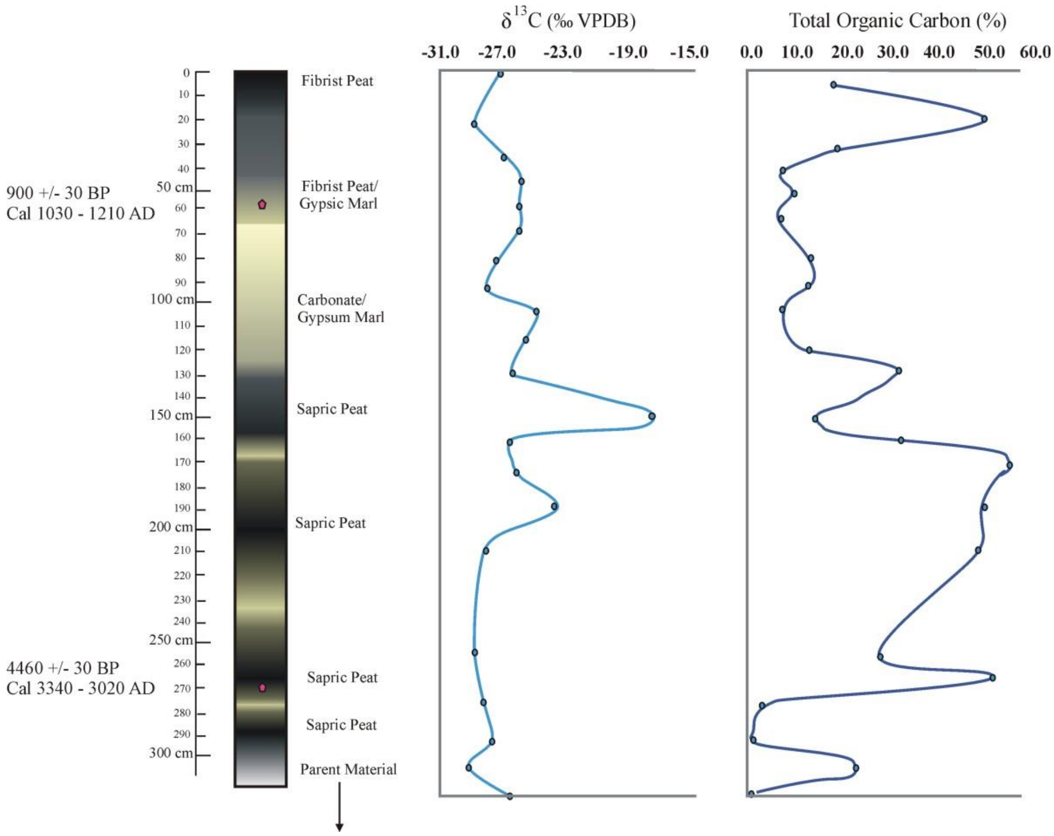

Figure 5.7. Ongoing work on the Laguna Verde Core.

5.8. CONCLUSION

The Akab Muclil core indicates three main geomorphic transitions based on multiple lines of evidence and the AMS chronology. First, the bottom of the core from 2.6 to 2.2 m is a terrestrial floodplain soil that formed in the Late Holocene. Second, at 2.2 m, during the Early Maya Classic (Cal 2 σ CE 255 to 420), the area started to become a wetland and steadily aggraded with anthropogenic signatures of eroded sediment, high amounts of charcoal and phosphorous, and pollen of economic species. Third, the upper1.4 to 1.1 m of wetland sediments lose most of their anthropogenic signatures until these rise again near the modern date at the top of the core. These paleoenvironmental changes correlate well with site archaeology. Artifacts and construction phases at Akab Muclil show that the site began in the Early Classic, and our wetland core provides side-by-side evidence that the wetland only started to form about this time. Below this Early Classic landscape manipulation lies a terrestrial soil within a natural floodplain. The swamp genesis began about almost 1700 years ago in the Early Classic and coincides with widespread use of the multi-hectare wetland agricultural system around it. A rising water table, either anthropogenic or natural, caused peats and sediments to deposit on top of the buried soil. About the same time, pollen and carbon isotopic signals indicate maize cultivation, which lasts through the duration of the Classic, with some intervals of cultivation into the Postclassic. This rising water table could be an indication of deforestation throughout the area, natural floodplain migration, or perhaps an intentional water management strategy given that the numerous ancient canals have a comparable history. Charcoal, possibly the result of managed burning, begins to increase as water table rises, as do levels of phosphorous and multiple lines of pollen evidence.

After the water table rises, cycles of stable wetland development (peats) and layers of calcareous deposition, as well as well-preserved ostracod and mollusk populations demonstrate that the system became a perennial wetland that correlates with Late Classic occupation at the site center. Tropical forest and water lily decline right after charcoal rises and disturbance species as well as pine expands with decreased tropical forest, which would have blocked their dispersal. *Zea Mays* is present throughout the Classic and probably into the Postclassic. Archaeological evidence demonstrates that regionally important site centers near Akab Muclil, such as La Milpa, Blue Creek, and Gran Cacao, all decline and depopulate in the Terminal Classic. Nonetheless, diminished agriculture persists as Akab Muclil maintains some construction into the Postclassic. After *Zea mays* becomes extinct above 120 cm in the core, wetland conditions and Poaceae, possibly from wetland grasses like *Phragmites australis* prevail until the present.

This local paleoenvironmental wetland study compared with local soil and archaeological research provides a richer picture of environmental changes which connects cause and effect in the system. Following the tradition of Butzer's human ecology and geoarchaeological methodology (1982; 2008), we are able to track this record of human intervention on the landscape by coupling geochemistry and paleoecology with adjacent archaeological studies. Moreover, grouping these local studies together can allow us to scale up to regional and larger scales that can give us insight into human responses to geographic transformations. Pollen signatures from throughout the region (savanna, tropical forest, and the increase of grasses and other disturbance taxa) coupled with localized macroinvertebrate populations (gastropods, mollusks, algae and ostracods) provide both a regional view of human-environment interaction and localized changes in water table, alkalinity, and wetland morphology.

With these varied proxies, we have demonstrated that this wetland was either naturally or anthropogenically derived and subsequently utilized for crop cultivation during the Classic Maya time period, which coincides with previous researchers who document an intensification of agriculture through this time period (Luzzadder-Beach et al., 2012; Beach et al., 2015a) and an increased dependence on wetland cultivation and manipulation due to some combination of population growth, increased trade, and shifts in climatic condition (Pope and Dahlin, 1989; Guderjan et al., 2017). Further, this system continued to be exploited for resources during some portion of the Postclassic, even during political changeover and cultural shifts. The present day geomorphology and hydrology around Akab Muclil has since persisted as a wetland since Maya abandonment.

Chapter 6: An Agroecosystem in Paradise: Reconstructing a Maya agricultural wetland on the Rio Bravo Floodplain, Northwestern Belize[4]

6.1 Introduction

The Birds of Paradise wetland (BOP) is a 6-8 km^2 forested wetland within the Rio Bravo floodplain in northwestern Belize, Central America. This wetland is a seasonally inundated fluviokarst system along the Rio Bravo that almost entirely lies within the Programme for Belize Rio Bravo Conservation and Management Area . The wetland is about 7-3.5 m above sea level and drains eastward into the coastal plain. Tropical forested wetlands have historically received less scientific attention than temperate systems, and research within wetland in this region is relatively scant. Further, the role that prehistoric populations played in the genesis of these systems is poorly understood. In 2016, we determined through a LiDAR survey that anthropogenic modification of BOP system was not only larger than previously thought, but that they system as a whole was more intensively managed by the ancient Maya than previously understood (Beach et al., 2018, forthcoming). This paper provides new geoarchaeological and geomorphic excavation within this wetland that focuses on human modification and management as well as soil and ecological development.

Our excavations in 2016 and 2017 provide a chronology of anthropogenic activity within the system. We use microcharcoal to develop a regional and local fire regime history, elemental geochemistry and paleoecology to understand wetland genesis, and

[4] Chapter 6 is currently (as of August 2018) being reworked in preparation for submission to a peer-reviewed journal. Timothy Beach, Sheryl Luzzadder-Beach, and Fred Valdez will be coauthors for this article, as they have helped me implement the fieldwork design for the 2016 season and are the PIs for funding sources, lab facilities and soil permits. In addition Timothy Beach is providing edits for writing and analyses. Colin Doyle and Katharine Bui will also be coauthors as they served as field and lab assistants.

carbon isotopes to understand human land use throughout the history of the wetland environment. Based on these multiple proxies and compared with regional climate records and Maya history, we are studying the timing, duration, formation, and spatial extent of human uses of anthropogenic wetlands. We also explore implications for ecologic and geomorphic change over the past 2,000 years in this system. These lines of data may further enhance our knowledge of human resilience and resource extraction in the face of long term regional drought cycles.

The BOP wetland complex was named for the presence of the false bird of paradise Heliconia found extensively along the banks of the Rio Bravo's floodplain throughout the system. We first surveyed and tested the wetland for anthropological features in 2006, but due to dense forest cover, difficult access, and seasonal flooding, we were only about to assess about .5 km^2 of the wetland area prior to the LiDAR survey in 2016. Following the LiDAR survey, we determined that a continuous canal and field system of over 4.5 km^2 was still visible within the modern wetland landscape (Beach et al. 2018 forthfoming). This research details our first excavations within new portions of this agricultural landscape to explore temporal and well as spatial connectivity of canals. Here we compare the eastern and northwestern extremes of anthropogenic features within the wetland using a variety of proxies including AMS dating, soil sequences and structure, organic content, carbon isotopes, geochemistry, and microcharcoal. This multiproxy geoarchaeological and geomorphological analysis provides new insight into the wetland's paleoenvironment and paleoecological change over the past thousand years as well insight into human use of wetland environments in this portion of the Neotropics during regional climate shifts.

6.2. Background/Regional Setting

6.2.1 Regional Climate and Drought History

Many studies have linked Late Quaternary climate reconstructions in Central America with studies of sociopolitical change of the Maya. Climate studies pay particular attention to drought and societal stress at the end of the Maya Late Classic, because of the time correlation of droughts and societal 'collapse' of the Maya civilization. The varying resolutions of climate proxy records and archaeological chronologies, along with a lack of written histories, however, make the changeover of this human-environment coupled system a complex story. There are a legion of possible explanations for the transition of the Terminal Classic, including varied land practices, differing regional response to precipitation change, cultural reorganization and strategy, and many more. Diverse resource use played a major, but still poorly understood, role in societal reorganization throughout the Classic and Postclassic. Further, it is becoming clearer from more LiDAR studies that wetlands and floodplains played an outsized role for subsistence and resource extraction during these key transitional cultural periods because of their cornucopia of resources especially during dry periods.

Much of the information we have on drought and climatic periodicity within the Maya world comes from lake cores in the Petén region, over 120 kilom southwest of our research at the BOP site (Rosenmeier et al., 2002; Hodell et al., 2005, 2008; Escobar et al., 2012). Additional limnological records come from Lakes Chichancanab and Punta Laguna in the central Yucatán Peninsula, north and east of our study site by ~200km and ~330km, respectively. There are also several key speleothem studies (Medina-Elizalde et. al., 2010; Medina-Elizalde and Rohling, 2012; Frappier et. al., 2014, Akers et al., 2016) that provide regional records for the Yucatán. Many of these droughts have been linked to factors such as the migration of the Intertropical Convergence Zone (ITCZ) and changes in El Niño frequency (Kennett et al., 2012). Most notably relevant to this study are the speleothem records from Macal Chasm in the Cayo District's Vaca Plateau, about 120km south/southwest of our study area, which linked major dry events in the region to time periods of cultural change within the Maya civilization, suggesting that dry spells were a factor for societal stress (Akers et al., 2016). The Macal Chasm speleothem record suggests that a substantial drying event occurred towards the end of the Terminal Preclassic (~1700 years BP), which generally agrees with drying from other climate records such as the Yok Balum speleothem (Kennett et al., 2012), Lake Chichancanab's Petén sediment record (Hodell et al., 2005) , and the Cariaco Basin record (Haug et al., 2001). This drying event is recorded in the Itzamna speleothem record, and it is hypothesized to have a precipitation change of over 50% relative to average amounts in the Yucatán Penninusla (Medina-Elizalde et al., 2016). The Late Preclassic drought preceded a period of relatively stable climate from the Early Classic through the majority of the Classic (Akins et al., 2016). Since this period marked a successful Maya transition through drought and earlier soil erosion, scientists have linked the growth of landesque capital in the forms of reservoirs (Beach et al., 2015; Luzzadder-Beach et al., 2016) and of soil conserving agricultural terraces with the beginnings of the Maya Classic (Beach et al., 2002; 2006; 2015). The Macal Chasm records two more droughts between 750-1200 years BP, which agree with dry periods recorded in Lake Chichancanab as well as the Yok Balum and Tzabnah Cave speleothems (Medina-Elizalde and Rohling, 2012; Kennett et al., 2012). Speleothem evidence indicates a precipitation decline ranging from 25 to 40% during these later droughts (Medina- Elizalde and Rohling, 2012, Douglas et. al., 2015). These events, starting in the Terminal Classic, are the start of a period of heightened climate variability across Belize and adjacent regions (Medina-Elizalde et al., 2010; Akins et al., 2016). These later droughts, most notably a severe drying event between 1535 to 1542 C.E, are recorded within historical records (Kennett et al., 2012).

Within the archaeological record, there is evidence of increased warfare and societal overturning at the end of the Maya Terminal Classic (Demarest et al 2004; Yeager and Hodell 2008; Kennett and Beach 2013). Gill (2000) hypothesized that societal destabilization within the region occurred in distinct phases based on water supply, with the western portions of the Maya civilization destabilizing first and the northern and central lowlands depopulating last. Indeed the lowland sites such as Mayapán appears to reappear after drought and strengthen politically in the Postclassic (Masson 2000, Aimers 2007) before also declining during societal stress correlating with a 15th C drought (Hoggarth et al., 2017, Paris et al., 2017). Much of the evidence for sociopolitical stress or resilience comes from archaeological efforts at urban centers throughout the Late Classic and Postclassic periods, but there is still little work that focuses on resource extraction and human-environment interaction from hinterland urban sites during these pivotal periods. Even scarcer, are direct excavations of agricultural zones and how the Maya used, abandoned, or reoccupied these places during Maya societal shifts.

6.2.2. Wetland Agriculture in the American Tropics

By now there is substantial research on prehistoric wetland farming throughout the Maya Lowlands and adjacent areas. Studies have documented expressions of floodplain farming and extensive earthworks throughout the Maya Lowlands. Similar systems of wetland agriculture occur throughout South America as well, most notably in the Llanos in Bolivia and Venezuela (Denevan and Zucchi, 1978; Lombardo et a., 2011;

Rodrigues et al, 2018), among other locations. These field and canal systems stretch over diverse geographic regions as well as vast differences in soil types and precipitation patterns (Renard et al., 2012). Currently, several projects are investigating the temporal, hydrological, and ecological implications of these Neotropical agricultural zones (Renard et al., 2012; Denham et al., 2016; Dunning et al., 2017; Beach et al., 2018, forthcoming).

The Maya Lowlands region stretches over the karstic and geographically low portions of Guatemala, México, and Belize. Research on prehistoric Maya farming systems reveals that a substantial amount of low and wet environments had been ancient Maya farms, planted to a variety of crops. The Maya exploited upland seasonally wet *bajos* and *rejolladas* for their temperature and moisture regimes and moist soils (Dunning et al., 2002, Munro-Stasiuk et al., 2014) they also farmed the periphery of coastal swamps (Jacob 1995). Perhaps some of the most extensively exploited agricultural areas, at least in this portion of the southern Maya Lowlands, were river floodplains, along which many researchers have documented, mapped, and tested unnaturally rectilinear canal features and associated field complexes (Beach et al., 2015). So far, field and canal systems along river systems are some of the largest swaths of remnant agricultural expressions within the Maya Lowlands (Siemens 1982; Baker, 2003; Beach et al., 2009; Guderjan and Krause 2011; Harrison Buck 2014), but only recently has multidiscipinary and multiproxy research come to the forefront of geoarchaeological and paleoecological thought and method when studying the form and function of these agricultural zones (Beach et al., 2015a; Beach et al., 2018 forthcoming).

6.2.3. Birds of Paradise: A Maya Agroecosystem

"In 2003, Sheryl Luzzadder-Beach rediscovered a kilometer square area of millennium old Maya canals in a remote wetland of the Belize-México border from a small plane" (Beach et al., 2018 AAG presentation). The first expedition into these fields occurred in 2006, with excavations of canals and fields. The canals showed up as rectilinear, relic canal features within a small patch of savanna vegetation along Cacao Creek, near its confluence with the Rio Bravo Floodplain. The BOP wetland is a seasonally inundated floodplain that lies along the Rio Bravo just 1 km after it emerges from the graben valley between the Rio Bravo and Booth's River escarpments. Both of these are the easternmost prominent scarps of a series of normal fault escarpments from the central Peten to the coastal plain. The rocks that make up these ridges are carbonates, limestone and dolomitic limestone. Groundwater seeping from spring sources along the escarpment floods the Rio Bravo with sulfur, calcium, and high TDS (Luzzadder-Beach et al, 2012). Runoff in the rainy season (May through December) dilutes the dissolved loads of these waters. This means that waters here strongly vary in dissolved load from the wet to dry seasons, even from dissolving to precipitating gypsum from the sulfate and calcium.

The vegetation at BOP is a mix of tropical lowland riparian vegetation and swamp vegetation, which includes woody trees such as Acacia spp., *Guarea excelsa*, *Pithecellobium belizense*, *Roystonea oleraceae*, and understory palms like Bactris spp. and Orbignya cohune (Brokaw et al., 1990; Bhattacharya et al., 2011). Other vegetation within the BOP setting includes sedges (Cyperaceae) and grasses (Poaceae) as well as bromeliads and epiphytes. The soils within this setting are deep and derive primarily from clay-rich alluvium, much of which originally weathered from limestone. The floodplain is aggrading at a rate of approximately 0.2 cm/y based on our previous findings (Beach et al., 2015a). Beach et al., (2015b) provided preliminary classifications for some of these soils, but younger soils have Mollic characteristics (dark, organic rich, high CEC, thick A horizons) or Histic characteristics (organic rich), whereas some older soils have Vertic characteristics (smectite clay, slickensides, parallel piped and wedge shaped peds). Most of the soils have pronounced gypsum masses due to groundwater flow and a seasonal water table with high sulfate and calcium.

We associate the canals and fields that make up the BOP agricultural zone with a handful of urban centers within the area. The well-studied site of Blue Creek lies about 5.5 km northwest of BOP. This center was active from the Middle Preclassic to the end of the Classic (2900 to 1000 BP), and several sources consider Blue Creek as the entity behind agricultural efforts at the nearby Chan Cahal wetland complex (Guderjan, 2007; Beach et al., 2015). Finally, the small site of Akab Muclil is directly adjacent to the north and east edges of the BOP canal network. Akab Muclil's occupation occurred from the Early Classic to at least the Terminal Classic, and had either continuous occupation or reoccupation in the Early Postclassical (Padilla, 2007, Krause et al., forthcoming). Since Akab Muclil is a relatively small center with no monumental architecture and Gran Cacao is much larger and nestled in BOP (the southwestern edge), we hypothesize that Gran Cacao was the main center that controlled and managed the wetland system.

The large urban center of Gran Cacao is on the southwest edge of the field complex. There have been limited archaeological excavations at Gran Cacao. This site is an urban center with a central plaza, ballcourt, and many enclosed elite buildings and temples. This site was first recorded in 1993 by Adams and Levi (Lohse et al., 2013). Some test pitting within the central plazas and nearby elite residences provide ceramic and architectural chronologies and place the urban center of the site as spanning the Early Middle Preclassic period through the end of the Classic period (Lohse et al., 2005) with some Postclassic artifact scatters throughout the upper levels of test pits (Durst 1996;

Houk et al., 2008). The general hypothesis regarding Postclassic occupation of Gran Cacao is that the area was abandoned at the end of the Terminal Classic, with a short and ultimately unsuccessful reoccupation during the earliest portions of the Postclassic. This narrative agrees with other sites in the area such as Akab Muclil and La Milpa (Sagebiel 2005, Padilla 2007, Houk et al., 2008).

6.3. METHODS

6.3.1. 2016 and 2017 Survey and Excavations

We excavated trenches placed over canals and fields as well as other anthropogenic features (a midden and a berm) throughout the BOP wetland during the 2016 and 2017 field seasons (Figures 6.2). The 2016 field season focused on an excavation (BOP 13) adjacent to previously surveyed and excavated portions of the agricultural system (BOP pits 1 through 12, previously discussed and synthesized in Beach et al., 2009; Luzzadder-Beach et al., 2012; Beach et al., 2015; Beach et al., forthcoming 2018). In 2017 we focused our excavations on areas that the LiDAR survey detected (BOPN1-3). We also field checked and sampled a raised berm area on the eastern side of the BOP wetland, and opportunistically placed a geoarchaeological test pit in a midden site near an architectural Maya mound on the northernmost extent of the wetland north of the Rio Bravo. All of these excavations took place in the height of the dry season, during which the water table was lowest and the area was most accessible.

Using a SM20 magnetic susceptibility meter, we collected field measurements of magnetic susceptibility (10-3 SI units) on flat soil surfaces in 5 or 10 cm increments over each soil horizon within the trenches. Each increment was measured three times and averaged. We then sampled the exposed profiles by horizons, collecting soil from each distinct horizon.

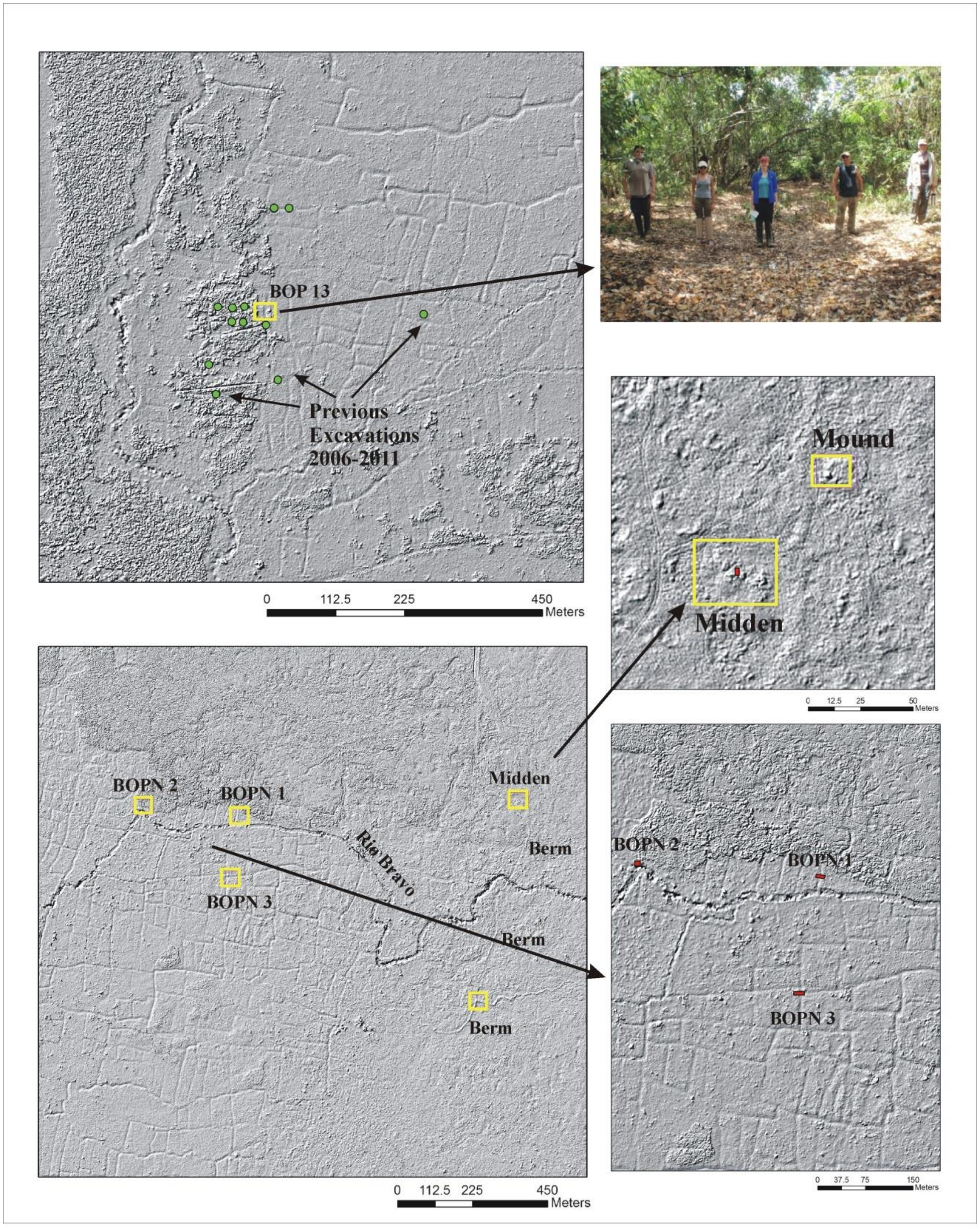

Figure 6.1. LiDAR map showing locations of test pits from 2016 and 2017.

6.3.2. 2017-2018 Laboratory Analysis

To understand the soil and wetland formation processes and the intensity and influence of anthropogenic activity in these zones, we studied the general characteristics of the soil horizons within these wetlands. I preformed bulk analyses of soil from each horizon within our test pit units, focusing on factors such as percent of organic matter and carbonate, total P, and magnetic susceptibility. I dried and combusted samples down profile for each excavation using the standard Loss on Ignition protocols developed by Dean (1974) and later by Heiri et al., (2001). After drying samples at 100°C we burned each sample at 550 °C to remove all organic material. I then burned the samples at 1,000 °C to remove carbonate, leaving only the non-carbonate inorganic contents behind. I also used magnetic susceptibility down profile of each unit, as soil can develop magnetic qualities due to a number of natural and anthropogenic processes, such as burning and deposition of magnetized sediments, or through biological processes and the breakdown of organic materials (Oldfield, 1999).

I measured extractable phosphorus from each of the soil horizons in our excavations (see Beach et al., 2017a; Krause et al., forthcoming). I use the Mehlich II method for extractable phosphorus in samples throughout soil profiles using a Hach DR/850 Colorimeter on the percent transmittance function at a wavelength of 690 nm (Terry et al., 2000). We then used a standard curve with known P concentrations to calculate each sample's phosphorus concentration.

Micro and macro charcoal studies are increasingly used in the Maya Lowlands and elsewhere to provide evidence for broad wildfire history (Wahl et al., 2013). Charcoal in wetland and lacustrine environments occurs in a variety of sizes. Microcharcoal is designated as a size fraction that is less than 180 µm. Mesocharcoal ranges from 180 μm to 1mm, and macroscopic charcoal generally is over 1mm in size (Scott 2010). In regional wildfire events, microcharcoal forms when surface fires transport ash and small particles (too small for taxonomic identification) into the air within smoke plumes (Peters and Higuera, 2007; Scott 2010). Research conducted by Higuera et al., (2010) found that microscopic charcoal best represent fires within a 1–3km radius of medium sized lakes. In addition, Innes and Simmons (2004) have reported that peaty wetlands and mires provide good preservation for microcharcoal, which is a good additional proxy for paleoenvironmental research of fire history and anthropogenic use of fire. In our study area, we consider frequency of charcoal within our soil pits. By coupling microcharcoal counts with archaeological information, AMS dating, and other proxies, microcharcoal can provide insight into anthropogenic fires from widespread clearing, deforestation, land modification events, or regional drying events.

For this analysis, I calculate charcoal concentrations based on previous methods used in the region for consistency and comparability (Clark 1988, Bozarth 2013). I removed clays and sieved the samples through a 180 μm sieve. I calculated charcoal concentrations by adding a known amount of spike spores (Lycopodium) to each sample before mounting on a slide. Two fractions of charcoal were counted, fragments between 10-80 μm and fragments 80 μm and above.

I measured carbon isotopes down profile in each unit using the humin fraction of the soil organic matter. I pretreated each sample using 10% HCL in a shaking hot water bath before extracting the humin fraction from the samples (Webb et al., 2004; Beach et al., 2017; Krause et al., forthcoming). I measured each sample using an Elemental Analyzer Isotope Ratio Mass Spectrometer housed in the Light Isotope Lab in the Jackson School of Geoscience and present all data in delta notation as per mil (‰)

relative to V-PDB standard.

We also selected a series of burnt charcoal samples from throughout each pit during the 2017 excavations for AMS dating. We found no viable charcoal from the 2016 pit, but we use dated stratigraphic units from previous adjacent pits to assume general ages of fields and canal features (Beach et al., 2018 forthcoming). International Chemical Analysis (ICA) ran all AMS dates for the 2017 excavations. We calibrated ages using INTACAL13, and we report all ages using 2 sigma calibration (95% probability). Conventional ages are in years BP (BP=Before Present, 1950 AD), and ICA corrected all ages for fractionation using the δ 13C.

6. 4. Findings

6.4.1. 2016 Excavations

In 2016, we placed a 7 m east-west by 2m north-south hand dug trench (BOP-13) on the top of a raised field, through a north-south trending canal depression, and into the top of an adjacent field top. We excavated this sequence to a depth of 200 cm, and ceased excavation when we encountered the water table. After this, we used an Oakfield corer to probe deeper into the substrate to determine if there were possible buried soil sequences below the water table, but the substrate was relatively homogenous below the water table. This pit follows the same general stratigraphy of other units excavated in this portion of the BOP wetlands, many of which have radiocarbon dating that suggests the canals started in-filling with sediment in the Terminal Classic/Postclassic (Beach et al., 2015; Beach et al., 2018 forthcoming).

BOP-13 followed the same general soil characteristics that are common within this type of wetland. The O horizon was a thin, 2 cm thick silt loam with many fine roots and dark organic material. Beneath the O horizon, there was a ~10cm thick A horizon followed by an A2 horizon with increased clay, more columnar structure, and characteristics of Vertisols. The percent of organic matter (%OM) in the A horizon is between 23.1 between 5-10cm and 33.3 between 10-15cm. Between 30-50cm in the field, and 60-120cm in the canal, we describe a mixed A/C horizon. Here OM drops substantially to between 11.4 and 4.4%. Following this level, we interpret a Cgy horizon where gypsum masses increase in the field areas, to about 30-40% gypsum within and along the sides of the canal. Below this is a darker buried A horizon (95-160cm in the field) of almost pure dark grey clay material and between 9.7-9.5% OM. Within the canal portion (center) of the profile, at the top of this buried A there is a dark organic and charcoal rich lens of activity, probably signifying the bottom of the ancient canal (115-130 cm), which has about 13.4% OM. At around 160 cm within this buried A horizon on the field sides only, we interpret a thin, ~3 cm lens of white, thick, clay as a possible burnt or ashy activity layer. This same activity layer was recorded in our excavations in prior field seasons (Beach et al., 2018 forthcoming). Below this from about 163 to 200+ cm, we report a homogenous 2Cgss horizon with characteristic slickensides, gley colors, and 8.9% OM. Within the northern field portion of the profile, we recognize crotovinas (possibly crayfish) that have mixed portions of the A and O horizon as deep as 90cm, but no such bioturbation occurs in other portions of the profile.

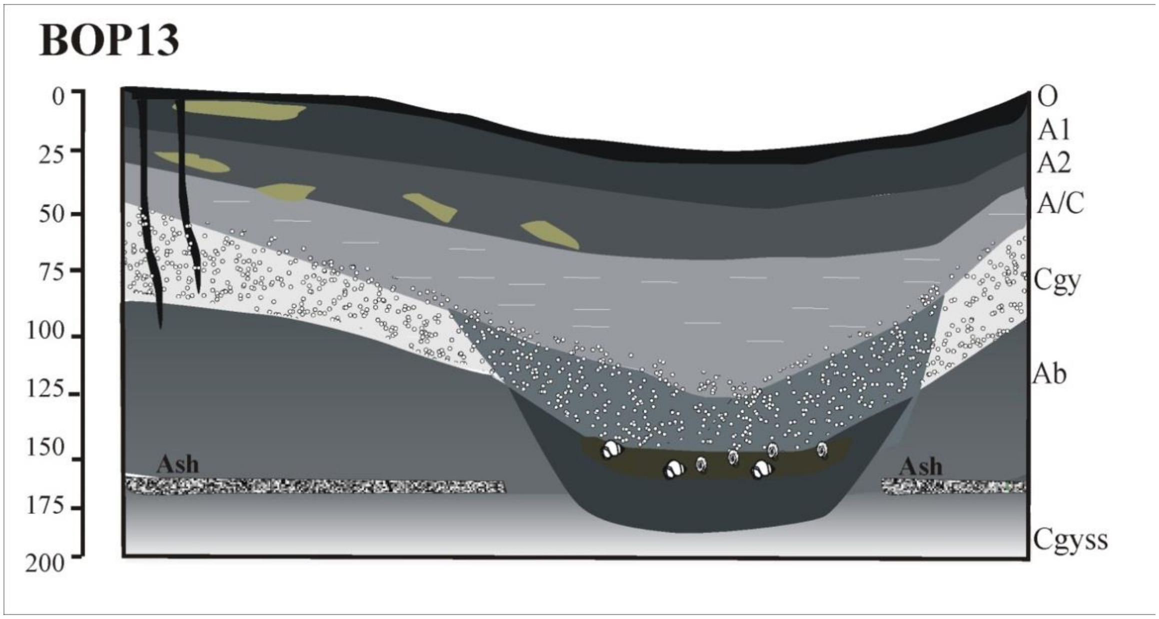

Figure 6.2. Stratigraphy of the BOP 13 pit.

We analyzed BOP13 to determine trends in carbon isotopes, magnetic susceptibility, P, and other elements (Table 6.1). Within the top soil (A1 and A2) horizon in both the canal and the field expression, the δ^{13}C value of the soil ranged from -29.1 to -30.1‰, which corresponds with a typical forested tropical wetland signal. Extractable P is at its highest level in these top levels, at 8.67 mg/kg, in the O horizon to 23.43 mg/kg in the A2. The δ^{13}C of the soil stays relatively heavy until about 65cm below surface in the field and 80cm below surface in the canal, where the value beings to shift positively by 3-4‰. In the buried A horizon (95-160cm) in the field portion of the pit, the δ^{13}C of the soil stays generally around -25‰, while in the canal from 105-120cm the values jump to -20.96‰. Extractable P in the buried A horizon is 6.41 mg/kg, and in the canal bottom P is 8.51 mg/kg. In the 2Cgss horizon on the field side the δ^{13}C of the soil is between -

27.1 and -28.59‰, and below the canal the 2Cgss has a δ^{13}C value of -27.9‰. The 2Cgss is much lower in extractable P, about 4.5 mg/kg.

Table 6.1. BOP Pit 13 geochemistry and isotopes.

Soil profile	Depth		Horizon	δ^{13}C	MS	%OM	%CaC 03	P	Al	Ca	Fe	Mg	S
	cm			%	10-3 SI	%	%	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg
BOP-13													
	0	2	O	-	0.023	23.1982	5.18018	8.6730	-	-	-	-	-
	2	12	A	-	0.008	33.333	4.483	6.1776	-	-	-	-	-
	12	30	A2	-29.10	0.0040	4.457	6.407	23.4371	-	-	-	-	-
	30	50	A/C	-28.60	0.0140	11.486	5.856	2.8942	-	-	-	-	-
	50	95	Cgy	-25.60	0.0300	13.483	5.618	0.8681	-	-	-	-	-
	95	160	Ab	-25.30	0.0387	9.729	5.656	6.4150	22,875.30	50,304.60	7,128.68	6,247.58	29,901.10
Canal Only	105	120	Canal Fill	-20.96	0.0027	13.483	5.618	8.5105	37,110.10	22,109.90	9,859.41	7,647.80	11,261.10
	163	200+	2Cgss	-28.59	0.0270	8.945	5.505	7.0842035	35,326.20	31,874.70	9,698.68	6,929.91	14,369.30

6.4.2. 2017 Soil Pit Excavations

In 2017, we excavated three new canal/field pits in new areas of the Birds of Paradise fields. The first pit we dug within a canal and field complex only 20 m away from the Rio Bravo, and only reached a depth of 100 cm on the field side before we reached the water table. We collected few samples from this location due to the rapidly rising water table and lack of datable material.

We placed the second pit directly onto a bend in the river to determine the characteristics of river bank and to search for any anthropogenic river modifications. This pit reached a depth of 80 cm (Table 6.2) and provides us with a natural stratigraphy of the river bank. Here the Oe horizon is between 0-4cm and consists of fresh and decomposing leaf litter and root material. The Oa is only about 1 cm thick below the O horizon, and is rich in organics (38.3% OM). Abruptly below this to a depth of 11 cm is a mixed A/Cy horizon, with 7.7% OM. Between 16-21 cm we describe a sharp transition to a Cy horizon that is very low in organics (5.1% OM) of powdery calcium and gypsum rich material. Below this horizon we describe a clay and organic rich dark grey Ab horizon that extends from 21-35cm and has 18.45% OM. This horizon transitions sharply to a tan/gray B horizon between 35 and 55cm. From 55cm to 80cm, where we ceased excavation due to close proximity to the river's water level, we describe a pure clay Cg horizon.

Table 6.2. BOPN-2 geochemistry and isotopes.

Soil profile	Depth		Horizon	Clay	$\delta^{13}C$	MS	%OM	%CaC03
	cm			%	%	10-3 SI	%	%
BOPN-2								
	0	4	O		-		-	-
	4	5	A		-26.41	0.001	38.3947	9.2065
	7	11	A/Cy		-	0.003	7.7732	25.8581
	16	21	Cy		-28.32	-0.008	5.1182	33.8525
	21	35	Ab		-	0.019	18.4575	5.5759
	35	55	B		-23.64	0.020	7.0059	6.6818
	55	80+	Cg		-25.30	0.100	-	-

The third pit, BOPN3, was a long trench stretching between two fields in an area in which there is a high-density of crossing canals under what is now high-tropical forest. We placed this trench strategically on a field top and into a north-south trending canal and then into an intersection with a long east-west trending canal. The pit was 5.5x1.5 m, and reached a depth of 160cm (Figure 6.4). On the western field side of the pit, above both the canal and canal intersection, we describe about 2 cm of O horizon, with many fine and coarse roots with about 50% clay matrix. Below this, we observe a relatively thin A horizon between 2-10 cm, which was highly organic, had granular structure, and continuing roots. The A horizon has a wavy lower boundary that transitions into a 1C horizon of carbonate sand. Below this, The A2ss horizon begins around 12-20 cm. This layer is composed of near-black slickensides with angular blocky (almost prismatic) peds of almost pure clay. Next, we describe an ACg horizon between 20-44cm, which has a prismatic structure and very fine root material, dominated by slickensides with no mottling. The lower boundary on this layer is somewhat wavy. From 44-68cm, we describe a Bw horizon, with massive clay and redoximorphic features, generally yellow and gray, as well as 10% sandy masses of decomposing rock material and streaks of charcoal. From 68-75cm, we observe the thin, light ash or burn layer consistent with many of our other BOP pits. Below this burn layer, the Abss from 75-95 cm is dense, black clay with slickensides, prismatic structure, and 5% limestone pebbles and gravels. From 95-120cm we describe an ACgss1, and below this a Cgss2 with low organic matter to the bottom of the pit.

On the east side of BOPN-3, which is the portion of the excavation that captures the canal expression, the soil profile is similar but does have key differences. Again we describe a surface O horizon with a mix of patchy carbonate sand and many fine roots throughout. Below this is the same thin A followed by an A2ss as described on the western field. From 26-34cm, we describe the ACg horizon that is thinner and more mixed in places here. From 34-63cm, we describe the continuation of the Bw horizon, again with increased charcoal and hydric soil features. At 55 cm, within this increased charcoal, we dated burnt material and acquired an AMS date of 1020 +/- 30 BP (Table).

Below this, from 63-77cm, is a mix of gleyed clay and gypsum. The gypsum increases with depth to cover 50% of the profile face in places. The layer is wavy at the top and bottom and dips down following the relief of the canal. This layer transitions into the Abss layer that is at a depth of about 90cm within the canal sequence. Below this from 90-105cm, charcoal and ash mix with the Abss; darkest portions are the bottom of the canal feature. There appear to be two canal bottoms within the profile, one being the bottom of the north-south trending canal and the eastern-most feature being the expression of the intersection with the east-west trending canal. We dated charcoal from the canal bottom (129cm) of the north-south trending canal, which provided a date of 740 +/- 30 BP, which is during the Maya Postclassic period. Below this, we describe an ACgss1 horizon between 105-125 cm composed of almost pure clay with slickensides, some dark organics, and low gypsum. The ACgss transitions around 125 cm to the bottom of the pit into a Cgss2 horizon, low in organic matter and again high in clay.

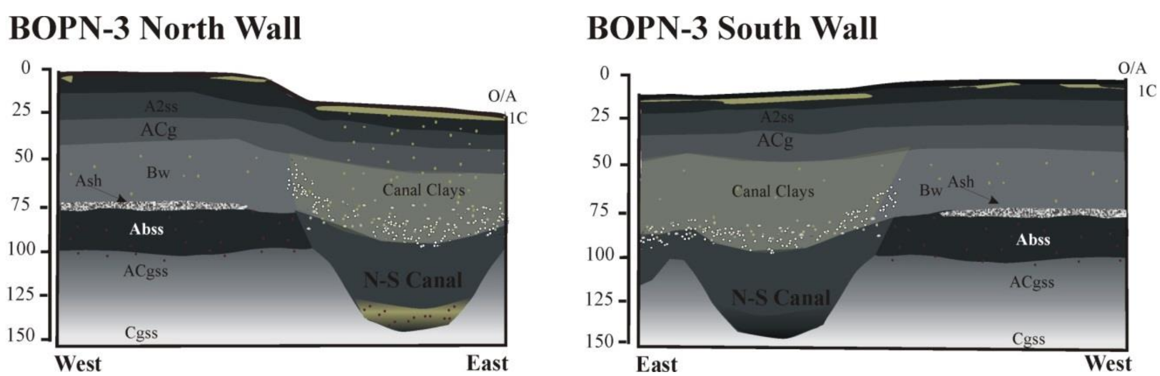

Figure 6.3. Stratigraphy of BOPN-3 pit.

The δ^{13}Cprofiles of the canal and field in this excavation shifts by several per mil throughout the profile, but in general provides a mixed tropical forest/tropical grass signal throughout (Table 6.3). Within the Bw horizon (34-64cm), the δ^{13}C of the soil

Table 6.3. BOPN Pit 3 geochemistry and isotopes.

Soil profile	Depth		Horizon	$\delta^{13}C$	MS	%OM	%CaC 03	P	Al	Ca	Fe	Mg	S
	cm			%	10-3 SI	%	%	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg	mg/Kg
BOPN-3													
	0	2	O	-	-0.029	-	-	-	-	-	-	-	-
	2	10	A	-	0.050	-	-	-	-	-	-	-	-
	10	12	1C	-		-	-	-	-	-	-	-	-
	12	20	A2ss	-30.11	0.036	6.5781	6.6972	3.7831	2,508.50	794,083.00	691.08	1,993.26	6,244.06
	20	44	A/Cg	-24.83	0.005	5.3374	19.5888	5.1276	36,709.80	27,208.20	10,869.50	7,069.19	16,386.20
	44	68	Bw	-23.8	0.100	6.071144	8.903284		25,934.80	93,382.90	8,334.52	4,598.37	13,289.20
Field Only	68	70	Ash	-	0.009	-	-	-	-	-	-	-	-
	75	95	Abss	25.55	0.039	5.3374	19.5888	4.1338	34,888.80	36,199.00	11,761.50	8,391.33	15,547.20
	95	120	ACgss1	-23.30	0.124	5.8629	4.0389		36,709.80	27,208.20	10,869.50	7,069.19	16,386.20
Canal Only	95	105	Canal Fill	-24.97	0.023	7.2013	5.8627	9.9382	28,298.50	47,319.80	9,020.90	5,751.61	10,404.80
	120	150+	2Cgss	-23.3	0.026	5.2768	7.8332	4.5251	-	-	-	-	-

ranges from -24.83 to -23.84‰. The Abss paleosol within the field portion of the pit has a value of -27.0‰. Below this the Cgss2 has a δ^{13}C value of -23.3. Within the canal expression of BOPN-3, the δ^{13}C value ranges between -24.3 and -25.8‰ from 85-100cm. Extractable P ranges from 3.7 mg/kg at the top of the profile. Within the middle of the mixed canal horizon, P ranges from 9.93 to 5.57. Extractable P is only 4.84 mg/kg below the canal sequence in the ACgss1 horizon.

6.4.3 2017 Geoarchaeological Excavations

During the course of the 2017 field campaign to ground-truth LiDAR, we located several small Maya mounds and a long, linear feature that seems to define the eastern extent of the BOP wetland field complex. We excavated next to one of the mounds on a burned Maya midden adjacent to the BOP canal complex. The midden was especially important for three reasons. First, there are simply too few midden features and roasting features that have been excavated from the Maya Lowlands region, especially from non-elite archaeological contexts, mostly due to poor preservation within this kind of tropical settings. There are only a few scholarly reports that have reported on midden features within this region (Wing et al., 1974; Shaw and Managan 1994). Second, throughout excavations within the Birds of Paradise system since 2006, we have only recovered a few small ceramic sherds and lithics within our soil pits, and the presence of this midden provides us with stronger evidence of timing and use of the canal system. Third, we can hypothesize that more such features exist within the system, and thus target future excavations to capture these kinds of features.

The BOP midden lies on the northern portion of the canal complex, within the modern savanna. This area is relatively clear due to seasonal fires, but has not yet been plowed in modern times, which we determined from personal communication with landowners. The midden itself is on a low rise (20-30cm above the surrounding ground surface) and is to some degree deflated.

Throughout the area, there were partially exposed piles of jute snail (Pachychilus) shells, many of which were missing the top portion of the shell. Previous research found that modern and ancient people, processed jute snails by breaking off the shell cones at about the third whorl, thus facilitating meat extraction (Healy et al., 1990). These kinds of shell remains are common within Maya sites from the Middle Preclassic until the Postclassic, throughout both the Southern and Northern Lowlands (Healy et al., 1990). We placed a 1x2 m unit oriented N-S by E-W on the center of the artifact and shell scatter on the highest portion of the midden and excavated in 10cm levels. The midden excavation revealed a 40cm unconsolidated sequence of ceramic sherds (many burned), small lithic fragments of chert and obsidian, limestone mano and metate fragments, dark organic soil and charcoal, as well as hundreds of bone and shell fragments. Field identification of bone fragments included deer, bird (probably turkey), as well as some small fish vertebrae as well and jute shells in the hundreds. Visual identification of the obsidian revealed that the majority of pieces were Ixtepeque, with only a few small curated pieces being El Chayal. El Chayal and Ixtepeque are the two dominant sources of obsidian for the region, with El Chayal being the main source during the Maya Classic and Ixtepeque during the Postclassic (Nelson, 1985; Rice et al., 1985, Nazaroff et al., 2010).

Below 40cm, the midden abruptly terminates. Below this boundary is a thick layer of loosely compacted carbonate sand that again abruptly terminates at 100-105cm. This kind of aggradation of material is most certainly anthropogenic in nature and represents a platform above the natural ground surface. Below this is a dark gray, clay-rich paleosol that begins to interact with the water table at around 120cm below surface. Within the carbonate sand matrix we recovered a long straight piece of wood that we interpret as a possible post for an ephemeral structure (Figure 6.4) and are in the process of using AMS dating to constrain the age of this post (data forthcoming).

International Chemical Analyses, INC radiocarbon dated a large fragment of charcoal recovered from underneath an overturned ceramic at 35cm within the midden pit. This charcoal dated to 820 +/- 30cal years BP (Cal 1160 - 1270 AD), which is an Early Postclassic date, supporting evidence of continued Maya use during the Postclassic, or possible re-entry and re-use of the wetland system for resource extraction, especially protein. The $\delta^{13}C$ value of the soil at 20cm below the surface was -24.49‰, represented a mixed vegetation, but under the ceramics at 35cm was -16.61‰, which is strongly indicative of the presence of C_3 species at this level. We also radiocarbon dated organic sediment (O horizon) at 110 cm in the paleosol below the carbonate sand layer, which dated to 1040 +/- 30 cal years BP (Cal 950 - 1040 AD), a Terminal Classic/Early Postclassic date that reinforces the hypothesis that this wetland was active as a resource extraction zone during time periods of cultural transition.

Adjacent to the midden and Maya mound is a raised linear feature that runs roughly N-S towards the Rio Bravo and then continues to run mostly south along the eastern-most edge of the canal and field system of the BOP wetland, with some offshoots that run east. The highest portions of the berm feature are at least 1 meveral m above the surrounding ground surface. This feature may be discontinuous in places and requires further survey and excavation in subsequent seasons. We placed a pit in a portion of the berm that had excellent surface expression (Figure 6.5). The top of this feature was a well-developed O and A horizon of about 15-20cm that is consistent with tropical forest soil development. Below this is an abrupt transition to loosely compacted carbonate sand from 20-140cm. This sand has subtle laminations of lighter and darker colorations, becoming more obvious around 80-90cm. There are thin lenses (~2cm) within the carbonate sand at 100cm and 130cm. Below 145cm, the sand transitions to a light, sticky gray clay with lenses of darker and lighter material throughout. There is a band of slightly more tan-colored clay from 180-190cm followed by a darkening clay from 190-205 cm. At 205cm, we describe a dark clay paleosol similar to the paleosol found at the bottom of the midden unit. There were no artifacts recovered from the berm unit.

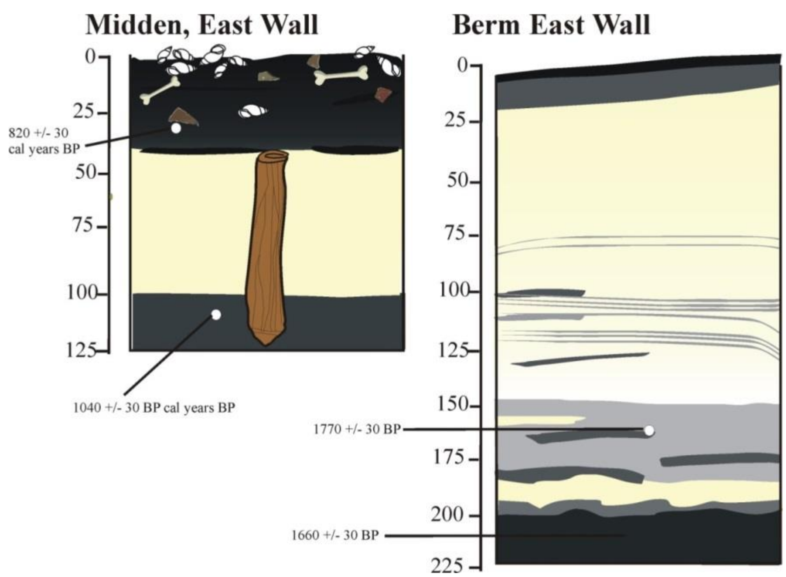

Figure 6.4. Stratigraphy of midden and berm.

We were able to date two sections of the berm profile. At 210 cm below surface, a charcoal sample dates to 1660 +/- 30 BP (Cal 320- 430 AD), within the Early Classic part of the Maya Classic. Above this, at164cm below surface, a charcoal sample dated to 1770 +/- 30 BP (Cal 130 - 350 AD), which stretches from the Late Preclassic to Early May Classic. We also measured the carbon isotopic signature of the soil components of the berm as the carbonate sand will not reflect the past vegetation, from 100cm to 245cm. The $\delta^{13}C$ values for this sequence range from -28.0 to -22.9‰ throughout the soil profile.

6.5. DISCUSSION

The temporal aspects of human modification of the western and northern portions of the Birds of Paradise wetland agroecosystem are similar, as are the soil formation factors and soil development since Maya abandonment, as is evidenced by the development of thick A horizon material on top of the berm feature as well as above ancient canal and field systems. On the western portion of the BOP system, our previous research demonstrates that the majority of fields became active in the system in the Late Classic and Terminal Classic, and canals began to infill with abandonment in the Terminal and Postclassic (Beach et al., 2018, forthcoming). Our new AMS date in the canal at BOPN3 agrees with this previous model, although portions of the stratigraphy of this canal is in some ways dissimilar to the stratigraphy of fields and canals on the western side of the wetland. The ash layers in the fields at both pits appear at different levels between BOP13 and BOPN3, and the levels of gypsum vary between pits, demonstrating localized differences in groundwater flow throughout the system. Charcoal levels within BOP13 and BOPN3 both show peaks within the Ab paleosol sequences, which can be linked to swidden or milpa farming practices during this time period, as well as Late Classic regional drying. BOPN3 shows a modern peak in characoal as well, which could relate to modern fire regimes and recent clearing for nearby agriculture. BOP13 does not exhibit the same modern peak in charcoal, possibly because it is located further into the modern day protected zone of Programme for Belize.

The soil morphology and geochemistry are dissimilar enough between canal and field excavations on the west side of the system (BOP-13) and excavations on the north side of the system (BOPN 1-3) to suggest differences in anthropogenic manipulation across this spatial scale (Figures 6.6 and 6.7.) The soil formation factors differ from one portion of the wetland to the next in several striking ways. One or more ash layers occur regularly throughout the system, which probably signify widespread burning events, These appear in different levels throughout the profile in the BOP13 and BOPN-3 excavations, as well as in earlier excavations such as BOP 2 with a burn ash layer at 225 cm that had 2 sigma calibrated age of 1183–1309 (Beach et al., 2015). We do not have radiocarbon ages for the BOP13 ash layer yet, but the layer here is at a depth of 160 cm, 85 cm lower than at BOP3N. All of these ash layers may be the same event or different events across the complex and may be deeper or shallower in the strata because the canal excavation was at different times, rates of sedimentation were different, or more or less ancient Maya field raising occurred due to hydrology and topography. The significant difference in ages between BOP 2 and BOP3N suggests that BOP developed as an agroecosystem at different times, and that canal creation was an event that occurred throughout the system's lifetime, rather than as one widespread event. The canals at BOPN-3 and BOP 13 plunge below the paleosol and the ash layer. There is also significantly more gypsum present in the field profile at BOP-13, which suggests that this area is hydrologically more active, and that perhaps seasonal flooding events cause more intensive sedimentation within the western portion of the wetland. The $\delta^{13}C$ profile in both BOPN3 and BOP-13 demonstrates a deviation away from C_3 vegetation during periods of Maya activity on the landscape, and this deviation is more pronounced within the canal sequences, where rapid infilling and sedimentation occurs. This could reflect the intensity of C_4 plant farming, especially maize, across this wetland, although we need more study to understand the intensity of maize cropping, as well as to understand the role that gypsum rich groundwater played within the agroecosystem, especially during times of drought like the ones occurring during the Terminal Classic-Postclassic periods.

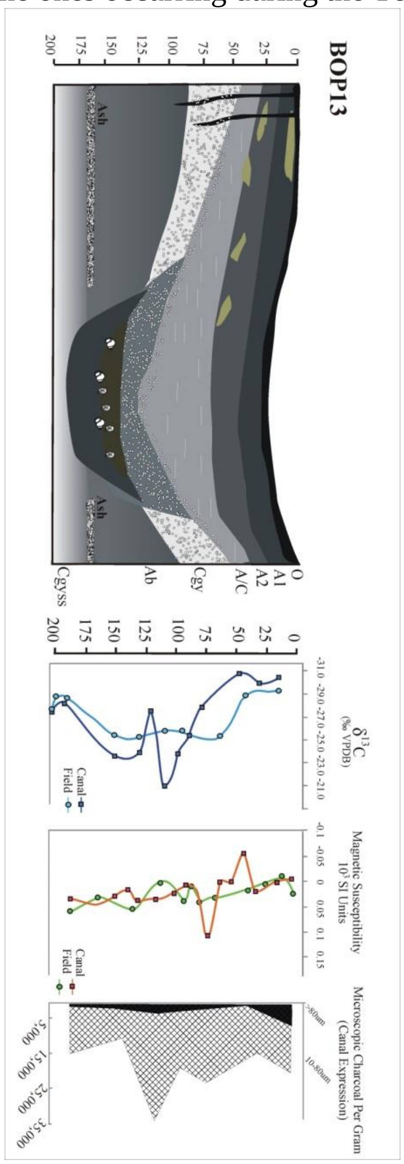

Figure 6.5. BOP excavation 13, stratigraphy, isotopes and magnetics from the field and canal and particulate charcoal from the field.

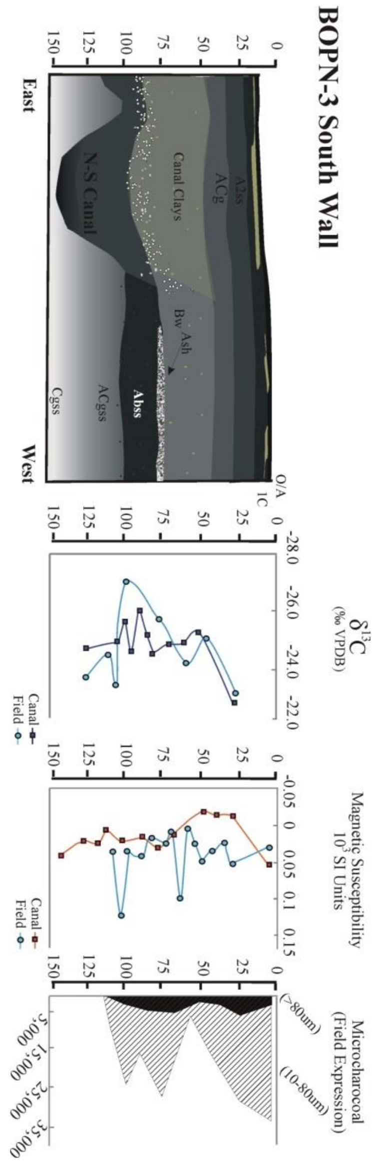

Figure 6.6. BOPN excavation 3, stratigraphy, isotopes and magnetics from the field and canal and particulate charcoal from the field.

The berm feature along the east side of Birds of Paradise system suggests that human modification within the system began at least to some extent sometime in the early Classic time period. The eastern margins of the BOP wetland are slightly lower in elevation than the area in the system that has been channelized, and it is possible this berm either acts as feature that serves as a boundary, eastern edge of a catchment, or elevated causeway in which farmers could enter the swampland from a raised pathway. The AMS dates on the berm 1660 +/- 30 BP (Cal 320- 430 AD, Early Maya Classic) and at 210cm and 1770 +/- 30 BP (Cal 130 - 350 AD, Late Preclassic to Early Maya Classic) at 164cm, are two out of sequence dates that possibly represent a construction event. As the berm was built up some time in the Classic, the builders piled up and packed sediments from older deposits above younger layers to raise the berm above the surrounding landscape. This earthwork appears to date before or at a similar time frame as the agricultural fields came into use, at least on the western and northern portions of the agroecosystem. We measured the $\delta^{13}C$ profile within the soil horizons of the berm from 100cm to 240cm, and find that the δ *value* shifts from -28.0 to -22.9‰ back and forth over the profile, which could be due to the variety of materials derived from different substrates that were thrown up and packed into the berm during construction (Figure 6.8).

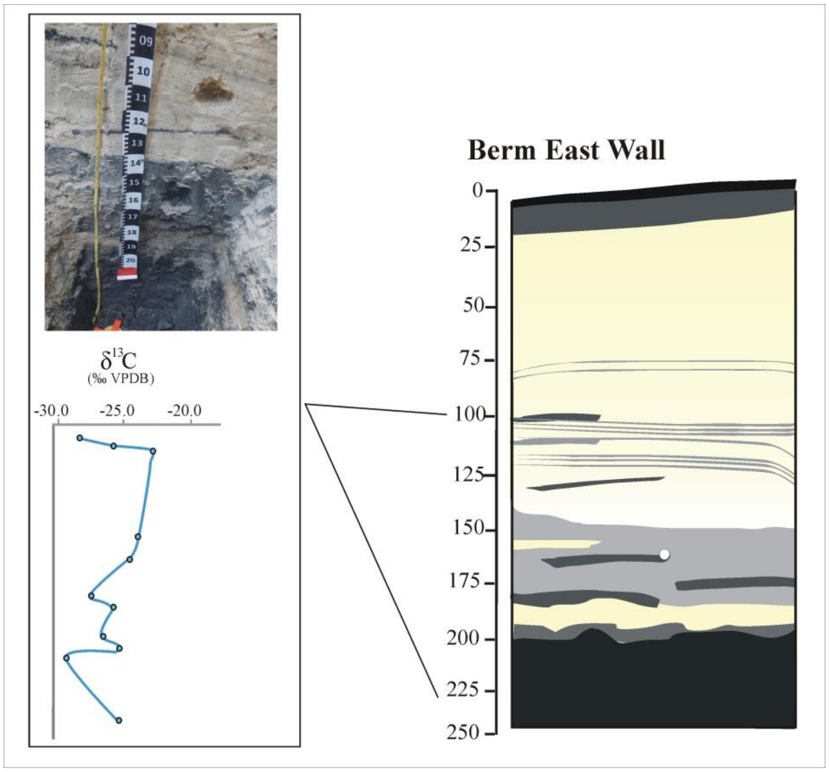

Figure 6.7. Isotopic profile of the soil deposits within the berm.

The presence of a midden at the extreme northern end of the wetland demonstrates the continued importance of the wetlands even after large nearby political centers were abandoned. By the Terminal Classic/Postclassic transition, the sites of La Milpa and Blue Creek, two key elite urban spaces, were no longer occupied. While some other site centers, such as the small community of Akab Muklil and the larger urban landscape of Gran Cacao, show evidence of Postclassic construction and use, the midden itself demonstrates intensive resource extraction and processing of resources from the wetland into the Postclassic time period. We suggest that the midden itself had multiple processing events, since materials spanned 40cm. We also suggest that the activity site was at least semi-permanent, due to the presence of posts as well as a platform on which collecting, processing, and cooking jute snails and other proteins occurred.

6.6. Conclusions

Neotropical wetlands are proving to have played an intensive role in agriculture among the Maya, and the Birds of Paradise system has played an outsized role in this region's subsistence during the Terminal to Postclassic periods. Here we have exponentially expanded our knowledge of the Birds of Paradise system as a heavily modified wetland that started as early as 1660 +/- 30 years BP with the construction of an earthwork berm on the eastern margin of the system. Clearing of the entire system began between the Late Classic and Terminal Classic; between 1350 to 1050 years BP, or AD 550-AD 950 (Beach et al., 2018 forthcoming). This clearing and channelization event was relatively short lived because canals start to fill up by the Early Postclassic. The variation of stratigraphy and sedimentation from the western to the northern sections of the wetland suggest that modification of the fields and canals may have varied by decades to a century based on dates at BOP2 and BOP3N. Radiocarbon dating suggests that the canals we have excavated in the system began to infill in the Postclassic, though intensive resource extraction continued into the Postclassic. Thus the wetlands and their adjacent centers persisted while urban centers throughout the region, such as Blue Creek and La Milpa, ended. Sites such as Akab Muklil remained active or became reoccupied alongside the Birds of Paradise fields into the Postclassic, and the scattering of Postclassic ceramics around the site of Gran Cacao were originally considered to be a re-entry after collapse of the socio political structure of the region. The continued intensive use reflected in the midden north of the BOP fields could suggest a larger presence of occupation and reliance on wetlands throughout the area than previously thought. Continued research within this wetland system should provide us with a tighter chronology to understand when human influence ceased within the Birds of Paradise, and insight into how wetlands re-wild in functions and ecological communities.

Chapter 7: Implications for Climate Change and Policy: How Are Wetland Protected, Degraded, or Restored in the Maya Lowlands?

7.1. INTRODUCTION

This dissertation has provided examples of how a variety of types of wetlands were an important socio-ecological resource for the indigenous Maya lowland culture for many millennia. Paleoecological and paleoenvironmental research within wetlands can help reconstruct the duration and intensity of human use over a variety of spatial scales, and studies like those provided in previous chapters can help provide a more holistic approach to current issues facing these environments. Currently, experimental studies looking at degradation and restoration within any natural environment are relatively short lived, and only provide researchers with a few decades of instrumental data. This cannot inherently capture the way in which a system responds to change over the course of the Anthropocene on its own. In reality, funding for restoration projects is limited and such projects are usually not monitored for more than five years after completion (Ruiz-Jaen & Aide 2005). By adding paleoenvironmental proxy data like the ones provided previously into these kinds of studies, we stand a better chance at modeling how systems impacted by human activity change over long periods of time. Paleoenvironmental research can be incorporated into work on long term biodiversity studies, regional hydrological cycles, and modelling carbon cycling and storage. This can provide the research community with long-term data sets by which we can model the role wetlands will have in future human subsistence and use as well as climate change scenarios.

In this chapter I review some of the ecosystem services that global wetlands provide as well as critical challenges wetlands face today. I then provide information on the current state of conservation and development within wetlands in the broader Yucatán region. I also synthesize current research on the state of natural and societal vulnerability in and around wetlands, as well as the challenges facing these complex landscapes today. Finally, I provide commentary on all of these challenges as they relate to the anthropogenic wetlands of the Maya Lowlands today.\.

7.2. Why Conserve Wetlands?

Wetland conservation is a growing field. Wetland across the globe are currently in various states of use, degradation, conservation, and restoration, and much of this work hinges on our ability to place some form of value on these systems, especially in regards to ecosystem services (Mitsch et al., 2014). Though often conservation and ecological scientists prefer to avoid assigning monetary value to landscapes, assigning value is an important and cross-disciplinary practice that allows for a critical assessment of these zones and what they can provide for both local societies and the global community. Some of the values we as a global society assign to wetlands relate to ecosystem services, which include such as flood control and storm surge buffers, biodiversity reservoirs, filtration, replenishment of groundwater and terrestrial carbon storage. There is a whole literature on how wetlands provide these services in a variety of systems across the globe.

In coastal areas, wetlands provide the aforementioned buffer zone in storm serve events, especially against tropical cyclones. Sheng and Zou (2017) determined through modeling that during the inundation of 1992's Hurricane Andrew in Florida, USA, a significant amount of floodwater was buffered from Miami-Dade County by the marshes and mangroves of Biscayne Bay. This study reports that the dissipation potential of floodwaters via mangrove forests is much higher than previously modeled, about 66% for hurricanes and other tropical systems that have similar strength and duration of Andrew

(Sheng and Zou 2017). During 2012's Hurricane Sandy, temperate coastal wetlands reduced flood heights across the northeastern coast of the USA, which avoided approximately $625 million USD in flood damages across the 12 coastal states that were affected by the storm. Even within heavily urbanized areas such as New York City, in which wetlands cover only about 2% of the land, estimations report that this small area of wetland saved approximately 140 million USD in urban repairs (Narayan et al., 2017).

Wetlands are also excellent sites for aquifer recharge. In their 2010 study in the High Plains region of the USA, Gurdak and Roe (2010) reviewed a variety of different studies that provide estimates of recharge through playa floors, and report that playas are able to recharge an aquifer between 0.25 to 600 mm/year. Researchers modeling types of surfaces and aquifer recharge in these same High Plains determined that the addition of playa surfaces has a small but statistically significant effect on well drawdown and recharge in some cases (Bian et al., 2013). Although aquifer recharge is considered an indirect service in that it has no definable monetary value due to the long temporal scale of recharge, (Bian et al., 2013) wetland system science as a whole should consider this particular factor with more scrutiny in the face of water scarcity in the future.

Aside from these aforementioned ecological services, wetlands serve as important geographical places of cultural heritage. Humans have been linked to wetlands for the duration of our time on this planet, as wetlands serve as persistent places in which a variety of resources can be gained (Ramsey et al., 2015). This kind of subsistence and use pattern and continued use occurs all over the globe, wherever humans settle. This dissertation has already provided a variety of case studies from the Maya Lowlands of Central America by which we can understand the ongoing coupled human-wetland systems within the region. But this is certainly not the only region in which humans have modified wetlands in lasting and significant ways, and on much longer time scales. Many of the Middle Paleotlithic (300–45 ka) sites in Africa are associated with former wetland margins (Nicholas 1998). Research around Lake Kinneret in Israel considers early hunter-gather's dependence on wetlands around the time of the Last Glacial Maximum (LGM) through the use of phytolith assemblages that suggest a reliance on wetland flora during adverse climate conditions (Ramsey et al., 2017). Similar studies in other locations around the Levant support this connection between humans and wetlands especially in regards to early cultivation (Rosen 1993; Ramsey et al., 2015). In the Neotropics, the lithic production site of Colha in Belize was located on the margins of a large wetland depression and was a site of dense occupation and region-wide economic production spanning at least the Maya Archaic (5000+ years BP) until the Maya Postclassic (1050 years BP) (Hester and Shafer 1993). All of these examples and more provide evidence by which we can consider wetlands to be an essential part of human lifeways over time.

7.3. Carbon Cycling and Wetlands

A growing but complex field of wetland system science includes the role they play in regards to climate relevant gasses, especially in regards to above and below ground carbon storage capacity, methane production, and the role of various types of tropical wetlands for global carbon cycling and turnover. There is some debate on whether or not wetlands, natural and anthropogenic, serve as a more significant sink for climate relevant gasses, or serve as a more significant source for climate relevant gasses (Cao et al. 1998; McCarty et al., 2002; Mitra et al., 2005; Xiaonan et al. 2008; Kayranli et al., 2010; Mitsch and Gosselink 2015).

There are five main carbon reservoirs within wetlands. These include plant biomass, particulate organic carbon, dissolved organic carbon, microbial biomass carbon, and emitted gas products, the major components being carbon dioxide and methane (Kayranli et al., 2010; Mitsch and Gosselink 2015). The organic carbon in a wetland is converted into compounds including carbon dioxide and methane or is taken up and stored in living plants, decaying plant matter, microorganisms, or peat and organic rich soil. Carbon accumulation and storage within wetland systems is dependent on the fluxes within that individual system. Soil disturbance, fluxes in water and nutrient availability, depth of water, and erosion are all factors that may change dramatically even annually. It is extremely difficult to quantify and compare wetland systems due to these differences, but also differences in biomass turnover rates, which relate to region and climate. Soil microbial biomass can be regarded as a significant but poorly studied carbon sink, especially within tropical wetland systems,

Current estimates contest that global wetlands can store up to 218 tons of carbon per hectare (218 t C ha−1) within these five carbon reservoirs (Bouillon et al., 2008), and much of the literature on terrestrial carbon pools and tropical wetlands focuses on different types of wetlands and the roles they play in global carbon. Some of the most studied types of wetlands in regards to carbon storage in the tropics are peatlands of various forms, (riparian, mangrove, and so on), though it is difficult to compare and quantity the roles that peatlands play because what scholars categorize as a peatland within the literature is not well defined (Lawson et al., 2015). A peat soil contains a certain amount of organic matter, but this value varies within the literature widely, between about 30 and 65 weight percent of the total organic matter (Joosten and Clark, 2002; Wust et al., 2003; Lawson et al., 2015). All of the current literature does agree that we still do not know nearly enough about how carbon cycling in these peat systems affects the greater global carbon cycle, and thus more on the ground research needs to occur in all of these systems. In Belize, for example, Page et al. in 2011 estimated there to be between 680 and 900 km^2 of peatlands and an additional 165 km^2 of shallow Histosols and organic rich soils, but with more survey and coring efforts this estimate is sure to be expanded.

Assigning a carbon stock value to a place is a fairly new concept. There are only a handful of studies that focus on tropical and sub-tropical wetlands and their carbon stocks in the Americas. Lawson and coauthors in 2015, for example provide an equation by which we can estimate the amount of carbon stored within a tropical peatland:

$$M_c=AD\mathit{pc}$$

In which M_c is the quantity of carbon in kg stored in a given region, A is the area of peatland in m2, *p* is the mean dry bulk density in kg m^{-3} and *c* is the dry mass of carbon concentration (Lawson et al., 2015). One of the biggest uncertainties for an equation like this is determining peat or organic rich soil thickness in any given region, and what the average SOM is within these layers. It is this kind of uncertainty that has made quantifying carbon sequestration within these kinds of systems so difficult.

It is estimated that soil carbon stock per hectare within tropical mangrove swamps is 214.4 t C ha^{-1} (tons of carbon per hectare)(Moreno-Casaola et al., 2016), carbon content in the aboveground biomass is 162.2 t C ha^{-1} and carbon content in the belowground biomass is 97.3 t C ha^{-1} (Siilamaki et al., 2012). In the Yucatán, Adame and coauthors in 2013 quantified carbon stocks for various types of mangroves (after computing a total for both above and below ground biomass), and found that the highest carbon stocks exist in tall mangroves at 987 t C ha^{-1}. Medium mangroves followed by medium mangroves (623 t ha^{-1}), dwarf mangroves (381 t C ha^{-1}), and marshes (177 t C ha^{-1}). In the nearby state of Tabasco, México, Moreno et al. (2002) calculated that carbon in mangrove soil was 471.9 t C ha^{-1}. Marín-Muñiz et al. in 2011 and in 2014 quantified the soil carbon stocks for freshwater wetland soils ranged from 150 to 310 t C ha^{-1} in freshwater marshes and from 225 to 520 t C ha^{-1} in freshwater forested wetlands in the state of Veracruz, México.

Agricultural activities within wetlands may increase the rate of carbon storage within the sediment, as it can increase accumulation of nutrients within the ecosystem, and wetlands that are cultivated (McCarty and Ritchie 2002). Conversely, anthropogenic activity may disrupt carbon cycling within wetland systems. Anthropogenic activities may hinder regeneration of natural vegetation, allow for species invasion, create imbalances of key nutrients such as P and N and thus even increase the cycling of carbon as well as accelerate carbon emissions (Wang et al., 2015). Hence, much research has focused on the usefulness of constructed wetlands for climate adaptation purposes. Some constructed wetlands in both temperate and tropical zones have proven to be effective carbon sinks, though they need to be designed correctly and maintained in order to keep them from being over productive methane sources (Rosli et al., 2017).

These studies on quantifying carbon sequestration within similar natural and anthropogenic wetlands can provide a starting baseline for adjacent study areas in Belize and throughout the rest of the Maya Lowlands. Further, by understanding the interplay between the various carbon reservoirs within ancient Maya agroecosystems and both the temporal and spatial scales of these wetlands, it is possible to assess their role as carbon and methane sinks and sources both past and present.

7.4. Development, Degradation, and Conservation of Wetlands in the Americas and American Neotropics

As previous chapters have shown, there is a growing body of literature concerning the prehistoric use of wetlands for agriculture. In the Neotropics and across the Americas, wetlands have been heavily modified to suit the growing needs of agriculturally dependent societies. Since European invasion, wetlands continued to be sought after landscapes for agriculture, but in radically different forms. In North America, the idea of wetland "reclamation" quickly took hold with European rule, which is the cultural concept that wetlands would be more productive landscapes if they were drained, diverted, or filled. This was the general practice throughout the Americas as modern farming was introduced, the federal government even provided incentives to drain and fill wetlands through the Swamp Lands Acts, which occurred in 1849, 1850, and 1860, which allowed for the wetland draining in states all along the Mississippi river and westward to reclaim land for agricultural purposes, though this was later deemed to be ineffective (National Research Council, 1992; Mitsch and Gosselink 2015). It wasn't until the mid-1900s that the US population began to recognize the negative impacts of widespread wetland modification and various groups began cooperative efforts for wetland conservation, mostly under the banner of waterfowl preservation (Mitsch and Gosselink 2015). This paved the way for current conservation and research efforts currently within much of North America. Throughout the Americas, one of the key players for wetland conservation is that of the Convention on Wetlands of International Importance, known generally as the Ramsar Convention. This was an international agreement signed in Ramsar, Iran in 1971, which now has 169 signatories, which was developed for the conservation and sustainable use of wetlands. Ramsar's ongoing work has provided the global community with a comprehensive definition of wetland classes, which even includes marine and anthropogenic classes of wetlands (Mitsch and Gosselink 2015). Some of key international players for South American wetland conservation include the Ramsar Convention and the International Waterfowl Research Bureau (IWRB)'s Neotropical Wetland Inventory from 1982-1984 (Naranjo 1995).

In México, recently steps have been taken to conserve and protect wetland landscapes. The key organization behind wetland protection across México is the Natural Protected Areas Commission (CONANP), which focuses on coastal areas and marshes, but the policies that CONANP is working on implementing are still new and will not be included in national legislation for some time (Fuentes et al., 2017). In Belize, most conservation zones are archaeological zones, wildlife sanctuaries, privately owned such as the Rio Bravo Conservation and Management Area (RBCMA) or set-asides for the management of resource use and extraction (Meerman and Wilson 2005).

Since wetlands play such key roles within environments globally, stakeholders at many levels are engaging in measures to sustainably utilize wetlands as well as conserve and restore them at various scales. Quantifying the value of a place is a tricky business, as there are a myriad of stakeholders and forces at play within any environment. Make that place a wetland, and you introduce the many natural fluxes and sensitivities to that already complex mix of factors.

Restoration ecology is still a fairly new field, and the purpose of restoration is to return an ecological area to a state of normal functioning that is integrated with the surrounding landscape that has similar structure of indigenous species as reference sites and is resilient to natural disturbance, among other criteria (Ruiz-Jaen & Aide 2005). Ruiz-Jaen and Aide (2005) analyzed 468 articles on the evaluation of restoration projects published within the journal *Restoration Ecology* and found that wetlands were among the most popular environments studied in regards to restoration.

Currently, the major factors and considerations at play when assigning value to a wetland are boiled down to whether or not it is worth more on a global or regional market when in an undisturbed state, in a developed state, or in a restored state. The growing realm of tourism within natural places is an interesting lens by which we can view conservation efforts worldwide, but it is possible that tourism and ecotourism are poor vehicles by which we can considering conservation of wetlands. One way in which wetland are conserved on a global scale is through national or state level parks, such as the Everglades National Park in Florida, USA. It can be difficult to acquire the kind of funding needed to designate wetlands with this kind of status. Buckley et al., (2012) determined that parks agencies across the globe rely heavily on tourism for routine operational funding, and while ecotourism at first glance may seem like a possible avenue for protecting critical biodiversity zones such as wetlands, there have been several studies that address the problems within ecotourism, but in that they can cause stress within critical and endangered species (Korman 2015), and also cause stress and harm within local and indigenous people (Mollett 2014). Historically, when it comes to the value of a place and how it should be used, indigenous knowledge or need has not been considered as part of the equation. There is a growing field of research regarding the expanding global popularity of ecotourism, conservation zones, or a coupling of these areas, and the displacement or lack of access of indigenous peoples within these spaces (Mollett 2014), but currently more scholars in these sectors are pushing for more intersectionality.

7.5. Where do we go from here?

There is an extensive literature regarding the significance and value of global wetlands, but there are multitudes of factors that must go into the policies regarding conservation and restoration of these zones. In the Maya Lowlands, wetlands are critically threatened by current farming pressures and increasingly severe drought regimes. The various wetlands of the Maya Lowlands are diverse in nature, and include riparian wetlands, peatlands, upland bajos, mangroves and coastal marshes, and each require unique management and conservation practices. Wetlands are already exceedingly sensitive and fluctuating landscapes, and it is certain that future climate change will make our efforts to understand and manage Neotropical wetlands more challenging. Wetlands are still one of the biggest unknowns within global climate models (IPCC 2001). This dissertation provides evidence that these zones have been altered for thousands of years by anthropogenic manipulation and intensive agriculture, which adds their value as heritage zones to the equation. With all this information, the question still remains of how shall we choose our priorities for wetland sustainability within the Maya Lowlands. How can possible future sustainability efforts assist with combating habitat loss and also benefit indigenous populations in this region? Within the wetlands of the Maya Lowlands, a variety of stakeholders will need to develop more intensive strategies for conservation if these landscapes are to be protected into the future, including land owners, governmental agencies, private sector entities and NGOs, as well as restoration, conservation, climate, and archaeological scientists.

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